ENGINEERING CASE LIBRARY

ECL 251

DIGGING INTO MARS

The mechanical design of the surface sampler or soil scoop for the Viking mission to Mars faced many uncertainties concerning the operating environment on Mars and the characteristics of the soil or rocks which the sampler would have to pick up. As a result, many difficult decisions had to be made by the project team during the course of the design and development effort. Conceptual design, engineering analysis, prototype construction and testing, and evaluation of alternatives were important aspects of the project. Told from the perspective of the manager at Martin Marietta Aerospace, Don Crouch, the case emphasizes decision making and project management, while also dealing in detail with the evolution of several of the hardware elements.

Prepared by J. A. Alic at Wichita State University, November 1977, with the support of grant No. SER77-02451 from the National Science Foundation. The cooperation of the National Aeronautics and Space Administration, especially Leonard V. Clarke of NASA-Langley, and of Martin Marietta Aeorospace, Denver, in particular Donald S. Crouch, is greatly appreciated.

DIGGING INTO MARS (A)

On July 20, 1976, at 4:53 AM (Pacific Daylight time), the first of the two Viking landers touched down on Mars. During the Viking I's second day on Mars, the surface sampler--or "soil scoop"--jammed, making headlines around the world. Because the primary purpose of Viking was to conduct a series of experiments aimed at the detection of possible life on Mars, failure of the surface sampler--used to pick up the Mars soil to be tested--would jeopardize the entire mission. Fortunately, the problem was solved and the Viking I sampler continues to function on Mars as of this writing. Likewise, Viking 2, which touched down on September 3, 1976, is still transmitting information to Earth, 50 million miles (on the average) away.

The story below describes several aspects of the design and development of the Viking surface sampler subsystem. Most of the work was carried out at Martin Marietta Aerospace in Denver, Colorado--principal contractor to the National Aeronautics and Space Administration (NASA) for the Viking project. Although the Viking landers were successful--and very sophisticated--engineering accomplishments, you should keep in mind that most engineering problems have multiple solutions--of which several may be equally successful--and that the design features adopted for Viking do not necessarily represent the only possible solutions to the problems the engineering team faced. Also included are comments by the case writer to fill out the chronicle, as well as background information.

GENESIS OF VIKING

The Viking mission is part of NASA's ongoing program for exploring the solar system. Among the planets, Mars has long been a subject of particular fascination; landing on the Mars surface could, hopefully, provide a final answer to the continuing question of life on Mars. While the Soviet Union had tried three times to land on Mars, on only one of these attempts--in 1971--did a spacecraft reach the surface. And, after 20 seconds, communication with this lander had been lost.

Efforts by the United States before Viking had been primarily fly-bys. NASA's series of Mariner spacecraft included three fly-bys of Mars, beginning in 1965, before Mariner 9 was placed in Mars orbit in 1971. The Mariners returned successively more data on the surface appearance and characteristics, as well as the atmosphere, of Mars. This data was an important input to the design and development of the Viking lander, and formed the basis of <u>Mars Engineering Model</u>, which gathered together information for this prupose. Mariner 9, for example, showed that surface temperatures during a "day" on Mars might be as cold as -135°F, while ranging up to +80°F. In addition to this wide range of

temperatures over time, the thin atmosphere also results in large temperature gradients between regions of sun and shadow, as well as vertically. Winds of 200 mph or more were also found to occur; these excite violent dust storms. Both the extreme temperatures and the expected wind-blown dust had important implications for the Viking surface sampler subsystem.

Engineering design for Viking began in 1969. The orignal launch target was 1973. However the launch was later postponed to 1975 (trajectories to Mars for which suitably low launch energies suffice are available only about every 25 months because of the relative orbits of Earth and Mars). Viking 1 took off from Kennedy Space Center, Florida, on August 20, 1975. Viking 2 followed on September 9, 1975.

THE VIKING LANDER

The Vikings were launched using multi-stage booster rockets. After reaching an Earth orbit at 115 miles, the spacecraft is aimed to achieve the desired trajectory to Mars. The last booster stage is then fired before separating from the Viking, which coasts for 310 days to reach Mars.

The Viking's own engines are used to achieve Mars orbit. The Viking itself consists of two vehicles--the orbiter, which remains in a highly elliptical, nearly synchronous orbit above Mars--and the lander, which descends using a parachute and retro-rockets. The lander is shown in Exhibit 1; details of the surface sampler subsystem have been excised from the drawing.

Cameras and instrumentation on the orbiter are used to locate a suitable landing site. The landing sequence begins with separation of the lander from the orbiter. The engines on the lander are used to slow its flight and to position it with the heat shield forward. At 19,000 ft the parachute opens; the lander separates from the parachute at 4600 ft and is further decelerated by the retro-rockets (terminal descent engines, Exhibit 1). Landing speed is 6 mph. Crushable aluminum honeycomb in the three landing legs cushions the touchdown.

Because the distance from the Earth to Mars results in a one-way video transmission time of about 19 minutes, the entire landing sequence--which takes only 10 minutes--is controlled by a computer aboard the lander (guidance, control, and sequencing computer, item 20 in Exhibit 1). Once the lander has descended, the orbiter itself continues to gather data, besides serving as a communications link between the lander and Earth. While all communications from Earth to the lander are direct, the lander can transmit to Earth either directly or via the orbiter.

Without fuel, the lander weighs 1260 lb (on Earth), about one quarter as much as the orbiter. Some idea of the complexity of the

Viking lander--and thus of the engineering effort involved in its design and development--comes from noting that it contains 750,000 individual parts. The total cost of the Viking mission was more than a billion dollars, while at any one time about 100 people were working on the design, development and fabrication of the surface sampler subsystem alone. Although Martin Marietta Corporation had the primary contract from NASA for Viking, many other companies participated in various aspects of the project. In addition, a large number of scientists affiliated with universities and government or industrial laboratories helped to design and implement the experiments carried aboard Viking.

The primary purpose of the Viking mission is to gather scientific data. Among the equipment (Exhibit A-1)carried by the lander for this purpose are the following:

-- a pair of high resolution video cameras made by Itek Corporation for examining the Martian landscape.

-- a meteorology boom carrying sensors for measuring atmospheric pressure, temperature, and wind speed and direction (TRW Systems Group).

-- a seismometer for measuring ground motion. The seismometer gathers data on meteorite impacts as well as geological activity (Bendix Aerospace).

-- a biology instrument for carrying out three different types of experiments on Martian soil samples, all aimed at detecting possible micro-organisms. The biology processor, Exhibit 2, receives material from the surface sampler and apportions it among the three experiments housed in the biology instrument, item 13. The biology instrument alone, developed by the TRW Systems Group, cost $50 million and represents 1000 person-years of effort. It weighs 34 lb.

-- a molecular analysis instrument to test for organic compounds in the Martian soil. This instrument is a gas chromatograph mass spectrometer (GCMS, Exhibit A-1. (Litton Industries.)

-- a mineral analysis instrument to analyze the inorganic constituents of the Martian soil. An X-ray fluorescence spectrometer is used for this purpose. (Martin Marietta Aerospace.)

The primary function of the surface sampler subsystem is to deliver soil to these last three instruments. Each instrument is a discrete unit located within the body of the Viking lander, with an opening on the top to receive soil samples as shown in Exhibit A-2.Each instrument can perform repeated experiments, allowing analysis of samples from several different locations within the range of the surface sampler.

In addition, the surface sampler carries magnets for studying the magnetic properties of the soil, and is also used for a series of studies of the physical properties of the soil such as porosity and bearing strength. For this purpose the sampler digs into the surface while forces are measured.

The science experiments, as well as the other equipment carried by the lander, are attached to or carried within a structure which consists basically of a hexagonal aluminum box (Exhibit A-1). The lander has a maximum width of about 10 ft and is 7 ft tall. Electrical power is supplied by thermoelectric generators which convert heat released by the decay of plutonium-238 to electricity. The lander carries a pair of these radioisotope generators, each capable of 35 watts output. For peak power requirements over 70 w, the lander can draw on nickel-cadmium batteries which are charged by the thermoelectric generators during periods of low power demand. The entire lander was designed to have a working life of at least 90 days on Mars. In actuality, the landers have operated in excess of 2 years.

SURFACE SAMPLER SUBSYSTEM

The surface sampler subsystem itself includes a number of subassemblies. Among these are processing and distribution assemblies (PDA's) for two of the experiments, the surface sampler control assembly (SSCA), and the surface sampler acquisition assembly (SSAA). The PDA's, required for the biology experiment and the GCMS, are visible in Exhibits A-1 & A-2. They grind and/or sieve soil to the desired particle size for the particular experiment, then feed the proper amount to that experiment. The SSCA contains electronics both for controlling the various components of the surface sampler subsystem and for gathering data from them. It receives commands from the lander's computer and "translates" these commands into electrical signals for operating hardware components such as solenoids and motors. As the commands are executed, the SSCA receives feedback data in the form of electrical signals related to positions of components (such as motor shafts), status of switches (off or on), and current levels. Among other purposes, such data is used to verify that commands have been properly executed. This data is transmitted to Earth as well as being used by the lander's computer. This computer, made by Honeywell, controls virtually all lander functioning and is thus termed the guidance, control, and sequencing computer (GCSC). It is designed with two completely independent sections such that if one section fails, the experiments can continue under control of the other. Similar redundancy is used elsewhere in Viking for reliability. For example, the SSCA has complete redundancy for control of the surface sampler subsystem, though not for data acquisition.

This case study deals primarily with the surface sampler acquisition assembly (SSAA). The SSAA has the job of picking up material from the Mars surface and delivering it to the experiments. Some of the design considerations for the SSAA have already been mentioned. The most important was reliability. Failure of the SSAA to deliver soil to the experiments would mean failure of Viking to perform its primary mission. Other considerations included capability for selectively sampling a relatively wide area around the lander, and the ability to survive severe environmental conditions both on Earth and on Mars. A wide sampling field was desirable to provide soil from different locations for successive experiments and also to get beyond the range of any possible contamination of the Mars surface by the retro-rockets during landing. A sampling range of up to 10 ft from the lander was the goal, although other distances were considered from time to time as the project progressed. The environmental conditions on Mars--including windblown dust and severe temperature excursions--have already been mentioned. On Earth, the SSAA would have to go through a sterilization cycle consisting of two days at 235 F to kill any micro-organisms which might otherwise be transported to Mars. Furthermore, no organic materials--for instance lubricating oils or greases--could be used anywhere in the SSAA where they might contaminate the soil being delivered to the experiments.

Another problem was the limited knowledge of the characteristics of the Mars surface. The Mariner photographs had only been able to resolve large surface features such as the channels on Mars. Thus the type of material the SSAA would have to pick up--whether dust, dirt, rocks, or whatever--was not really known. The Mars Engineering Model outlined a number of contingencies for which the SSAA had to be prepared, including sand, gravel, "lunar nominal" (a high cohesive soil made by crushing rocks to powder which simulates the surface characteristics found on the moon), and loess (a type of loam found on Earth containing sand and clay). A final important constraint for the SSAA--as for all components on Viking--was weight. The initial target weight for the SSAA was 20.1 lb, although this was later changed.

Instruction A

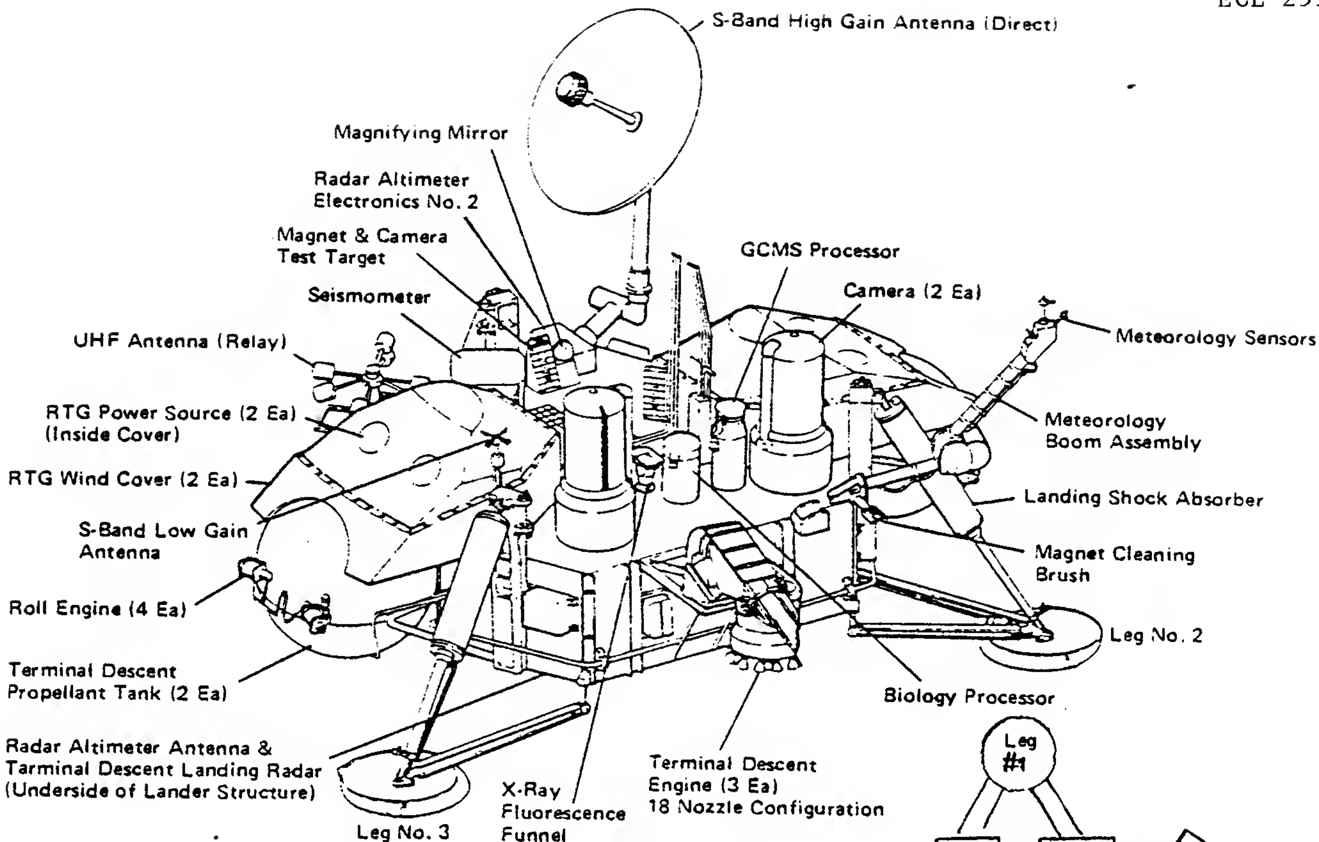
At this point you have much of the information the design team for the SSAA had in 1969 when they started on this project. You should begin a design notebook to record your work as you progress through the case study. A design notebook is a convenient way of organizing and recording thoughts, concepts, calculations, sketches, and other information pertinent to an engineering project. It is a valuable aid to thinking, as well as a document of potential legal value, for example in establishing patent claims. For this and other reasons, all entries should be dated.

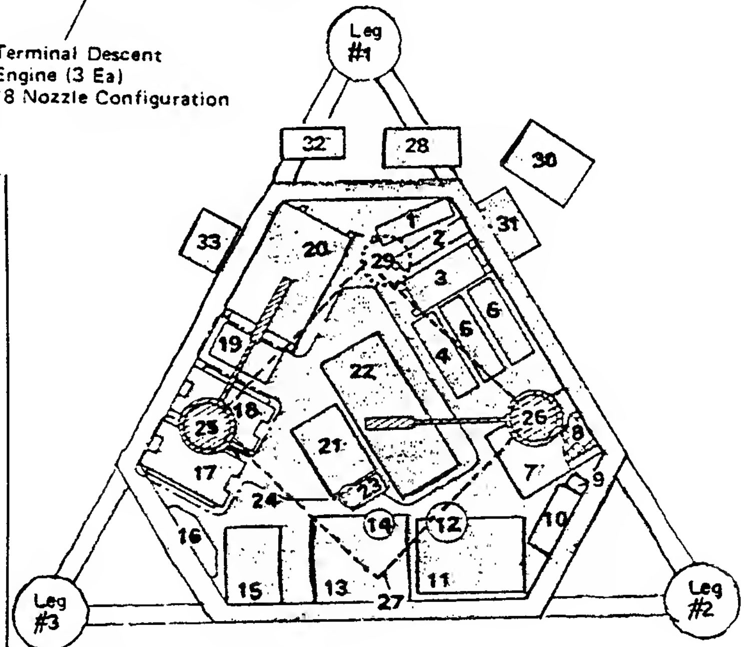
The first entries in your design notebook should be the problem definition and a summary of constraints or design requirements for the SSAA (only) as you understand them. These entries should be based on the discussion of the Viking project above, but written for you, in language you understand, to help you in thinking about this problem.

When your instructor has looked at and approved your problem definition and list of constraints, go on to think of alternative design concepts for the SSAA. Strive for many ideas and for concepts which are fundamentally different from one another. Do not worry too much about details at this stage. Your goal should be to ensure that no potentially feasible surface sampler design escapes scrutiny, for only by exploring all possibilities can you be sure that the final design is good. Many successful designers find that the best ideas come only after they have struggled with a problem for a while. You should expect this stage to extend over several days and--though this is a frequent temptation--not be satisfied with the first thoughts that come to mind.

Record your ideas in your design notebook using freehand sketches. These sketches can be crude, but should be at least good enough to remind _you_ later of what your idea was and to help you explain it to someone _else_. Notes or written descriptions can also help to define your thoughts. Use plenty of paper and make nice big drawings.

The purpose of sketching is not only to record your ideas but to aid in formulating them. You should find that the very act of sketching causes new ideas to come to mind--either modifications to or variations on the sketch you are making, or completely new thoughts. This use of sketching as an aid to visualizing new concepts is at least as important as the recording function of the sketches.





(Viewed From Top of Lander)

Item	Subsystem/Components
1	Transponder No. 1
2	Transponder No. 2
3	Command Control Unit
4	Microwave Components
5	Travelling Wave Tube Amplifier No.1
6	Travelling Wave Tube Amplifier No.2
7	Data Storage Memory
8	Tape Recorder
9	Ambient Pressure Transducer
10	Meteorology Electronics Assembly
11	Gas Chromatograph Mass Spectrometer
12	Gas Chromatograph Mass Spect. Processor
13	Biology Instrument
14	Biology Processor
15	Surface Sampler Control Assembly
16	Camera Duster Assembly
17	Battery Assembly No.1
18	Battery Assembly No.2
19	Ultra High Frequency Radio Assembly
20	Guidance Control and Sequencing Computer
21	Data Acquisition and Processor Unit
22	Power Conditioning and Distrib. Assembly
23	X-Ray Fluorescence Spectrometer
24	Radioisotope Thermoelectric Generator Coolant Loop
25	Thermal Switch No.2
26	Thermal Switch No.1
27	Thermal Descent Landing Radar
28	Inertial Reference Unit
29	Radar Altimeter Antenna
30	Valve Drive Amplifier
31	Radar Altimeter Electronics
32	Lander Pyrotechnic Control Assembly No.1
33	Lander Pyrotechnic Control Assembly No.2

Exhibit A-1. Viking Lander (Surface Sampler Details Omitted).

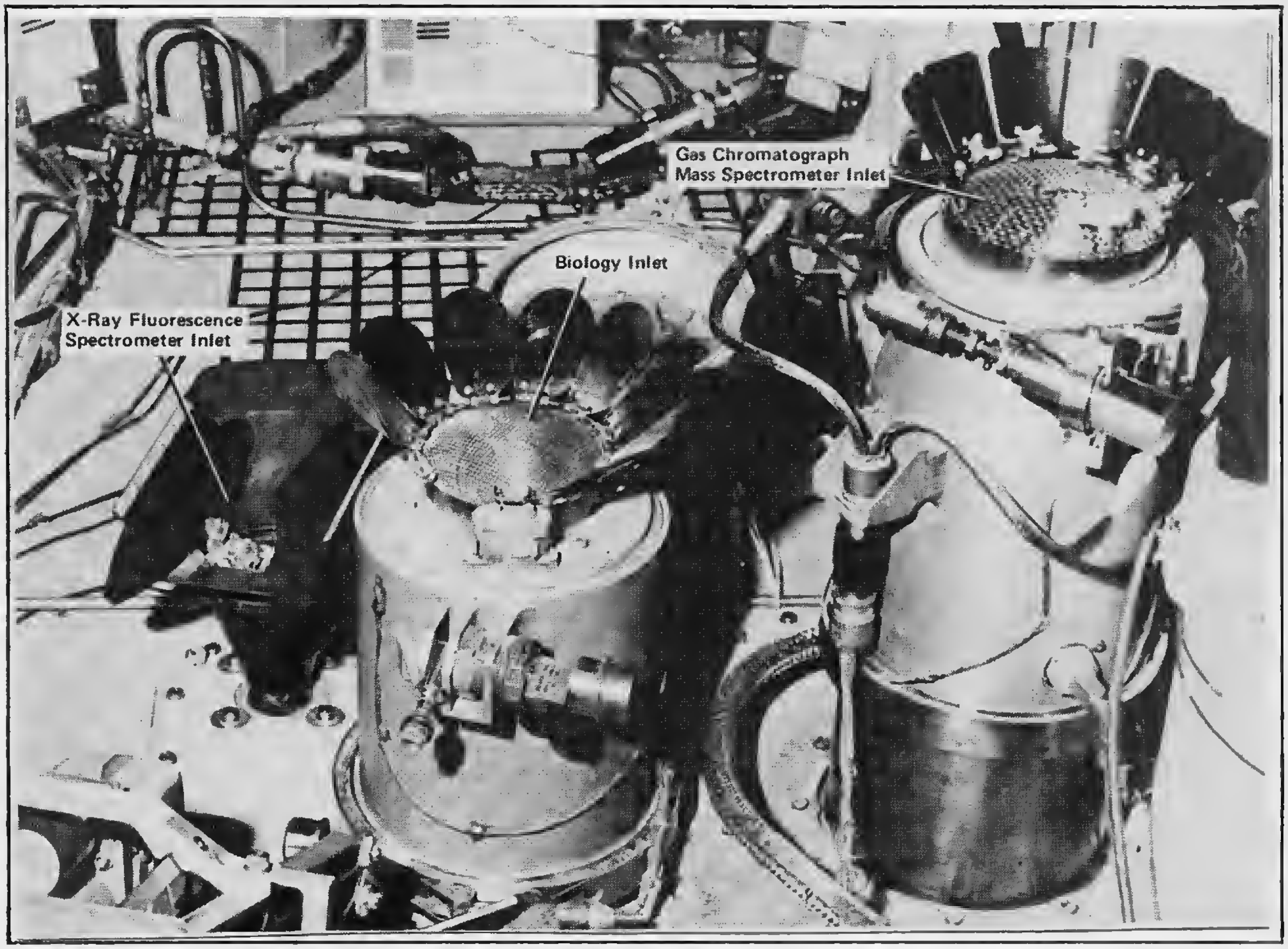


Exhibit A-2. Inlets for Delivery of Soil from Surface Sampler to Science Experiments.

DIGGING INTO MARS (B)

The design team working at Martin Marietta Aerospace in Denver on the surface sampler subsystem was headed by Donald S. Crouch. Much of the rest of the story of the surface sampler acquisition assembly (SSAA) will be related by Mr. Crouch. Other portions will be quoted from or based upon several of the dozens of technical reports which document the development of the SSAA.

Don Crouch was educated as an electrical engineer at John Hopkins University in Baltimore. While still in school in the mid-1950's, he began working for Martin Marietta in Baltimore, and, except for military service, has been with the firm ever since. Don said, "I first got involved with the space program by working on the lunar drill for the Apollo missions. Then, after Apollo, I sort of fell into the sampler for Mars. The Apollo drill was hand-held by the astronauts and brought up a 10 ft core sample. This was quite different from the Viking requirement, but still gave us some background for sampling on Mars."

"At that time--1969--the entire specification from NASA for the Viking mission was only about 15 pages long," Don continued. "The basic requirement for the soil sampler was to deliver an uncontaminated, unheated sample of so many cc's and of a given particle size to the three experiments."

"Our baseline design for the surface sampler was a scoop of some sort on the end of a boom. The Surveyors--which landed on the moon in 1967 and '68--had a system like this. The Surveyor boom was just an arm about three feet long, with a backhoe on it. This was used to dig trenches and pile up material for the soil mechanics experiments. However the Viking requirement was much more demanding. We needed a ten foot boom, and in addition to digging into the surface and pushing rocks around, it had to collect the samples, bring them back to the lander, and deliver them to precise locations at the inlets to the science experiments. During 1969 and 1970 we looked at quite a few concepts for accomplishing this, particularly at alternative boom designs. All of these involved booms which could be extended and retracted from a gimballed mount on top of the lander. With a high enough mount and rotation about both horizontal and vertical gimbal axes, we would be able to cover quite a wide sampling field."

At this time the functional and design requirements for the SSAA included the following:

- Sampling Area: 3 to 10 feet, 120° arc (the relatively large sampling area, about 100 ft^2, was desired by the scientific teams planning the lander experiments).

-- Sampling Depth: 0 to 4 cm or 4 to 10 cm by command.

-- Sampling Volume: 8 samples, each 1 to 1.5 cc, to GCMS (gas chromatograph mass spectrometer for organic analysis); 4 samples of 6 to 8 cc to biology experiment; 10 samples of 25 - 35 cc to the x-ray fluorescence spectrometer.

-- Sample Temperature: not heated above 35°C.

-- Temperature Transducer: mounted in collector head (gives an electrical signal proportional to temperature).

-- Mars Operations: 30 operational cycles.

-- Contamination Control: in accordance with PL-3701045 (a specification dealing with cleanliness and sterilization).

-- SSCA Operation: responds to serial binary commands from GCSC. (The SSCA, or surface sampler control assembly, is controlled by the Viking computer--the GCSC or guidance, control, and sequencing computer--by means of electrical signals. These signals consist of sequences of high and low voltage levels corresponding to ones and zeros--thus serial binary commands.)

-- Operating Attitude: 0 to 35 degrees from local vertical.

-- Engineering Surface Models: lunar nominal, loess, lag gravel, dune sand, and their combinations.

-- Magnet Array: required in collector head.

-- Safety: overload devices to preclude boom overloads.

Instruction B

Explore a variety of conceptual designs for the SSAA boom in your design notebook. Do not worry too much at this time about details or about meeting specific design requirements. Rather, concentrate on generating many different designs for booms which can be extended and retracted. Record your ideas using sketches and notes. Select one or more of these as worthy of further development and make more detailed sketches of it.

DIGGING INTO MARS (C)

During 1969-1970, a number of different boom designs were considered by the Viking SSAA engineering team. Several of these design concepts are discussed below.

1. Telescoping Boom--Exhibit C-1. This design consisted of a set of nested rectangular tubes pulled in or out by flexible metal tapes driven by a pair of electric motors.

2. Tri-Pantograph Boom--Exhibit C-2. Three pantographs arranged to give a triangular cross-section are extended or retracted by a motor-driven leadscrew. Each pantograph is a truss consisting of a series of X-configured panels.

3. Furlable Tube Boom--Exhibit C-3. The drawing shows cross-sectional views of the boom. When the boom is extended, its cross-section is a circular tube consisting of a pair of overlapping segments, each of which spans an arc of 320°. The segments consist of long strips of thin (.010 in.) stainless steel which are formed to a circular shape. (Type 301 is a common stainless steel alloy containing about 18% chromium and 8% nickel, most of the remainder being iron; on the drawing CRES stands for corrosion resistant steel.) The circular cross-section gives good rigidity even though the tube walls are very thin. When retracted or stowed, the two strips are flattened by a system of guides and rolled up on a drum, one on top of the other. The strips can be flattened without damage because of their low thickness.

   "A number of different furlable boom designs were available to us," Don Crouch recalled. "I believe that the concept was first developed by Ryan Aviation back in the 1950's. The idea is like that of a tape measure which has a curved cross-section when extended, but flattens out when rolled up. Furlable booms of various types have been used for antennas on a number of satellites and other spacecraft. We contacted several companies that make these booms to get their proposals." The design shown in Exhibit C-3 was one of a pair of "Bi-Stem" booms proposed by Spar Aerospace Corporation, a Canadian firm.

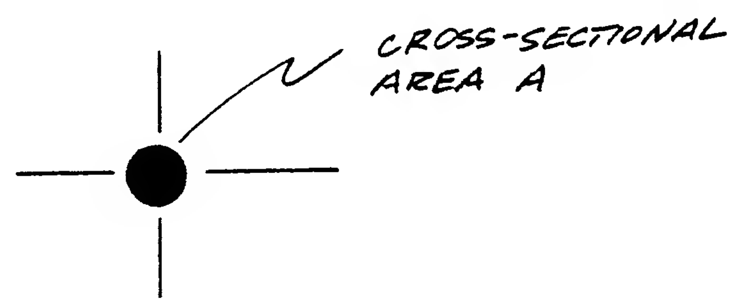
4. Single Segment Boom--Exhibit C-4. This boom is simply a long, straight tube--of elliptical cross-section for maximum rigidity under bending loads--which can be moved in and out. It would be mounted and stored on the lander as shown in Exhibit C-5. This figure also conveys the general arrangement--though not the details--of the mounting for any of the boom units, as well as the sampling area for any 10 ft boom with this mounting location. The two narrow regions about 60° apart and otherwise within the nominal sample acquisition area are out of the view of one of the two cameras, hence not useful.

In addition to the four designs described above, a number of variations on these themes were considered. Some thought was also given to combining the SSAA with the meteorology unit, using a single boom rather than separate booms for each.

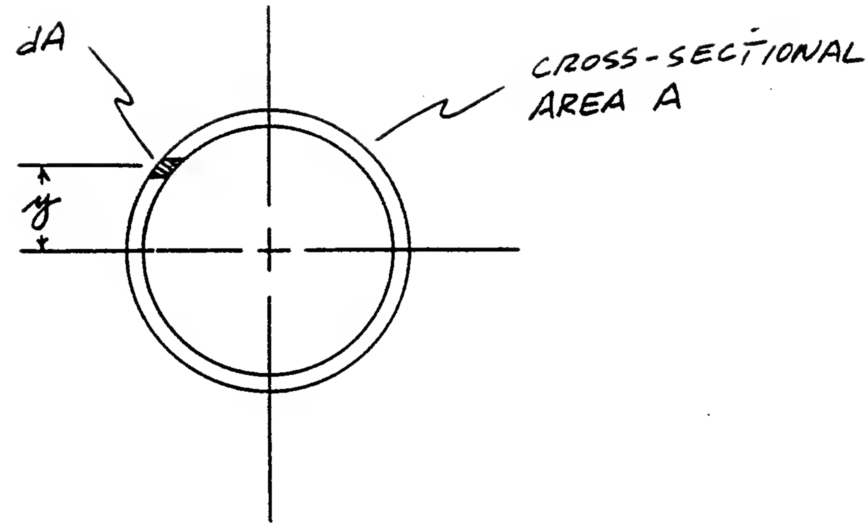
From the discussion above, it should be clear that important considerations in evaluating and comparing proposed boom designs were their strength and rigidity. Both strength and rigidity depend in general upon the cross-section of the boom. For example, let us consider the stresses and deflections created when digging into the Mars surface. As the scoop at the end of the boom is forced into the ground, the boom will bend. At the inboard end of the boom, the bending moment that must be resisted is equal to the digging force perpendicular to the boom multiplied by the length of the boom.

This bending moment determines both the stress and deflection for a boom of given cross-section. Basically, the stress in the boom is a measure of how much force must be carried by a given portion of the cross-sectional area. The higher the stress, the greater the force being "transmitted" through that portion of the cross-section. When the stress reaches a critical value characteristic of the strength of the particular material, the boom may fail by taking on permanent curvature, or, at even higher stresses, by breaking. However there are other ways in which a structural element such as the boom can fail. One of these, crippling or local buckling, we will encounter later on. For some of these possible failure modes, a parameter other than stress may be important.

The weight per unit length of a boom made of a particular material--e.g. stainless steel or aluminum--depends only upon the cross-sectional area. However different cross-sections of the same area may differ greatly in their stresses and deflections for a given bending moment. A solid circular cross-section



is much less resistant to bending than a hollow tube of the same area.



(Flatten out a soda straw and its resistance to bending is greatly reduced). Basically, the further away from the center line or axis of the boom the cross-sectional material is located, the greater will be the resistance to bending. The relations can be quantified using the moment of inertia of the cross-section, I, defined by $I = \int y^2 \, dA$. In this equation, y is the distance from the centroid (often coincident with the geometric center) of the cross-section to a differential element of area dA. We see that I goes up with the square of the distance from the cross-sectional material to the centroid of the boom. The stress at a given location in the cross-section is calculated from

$$\sigma = \frac{My}{I}$$

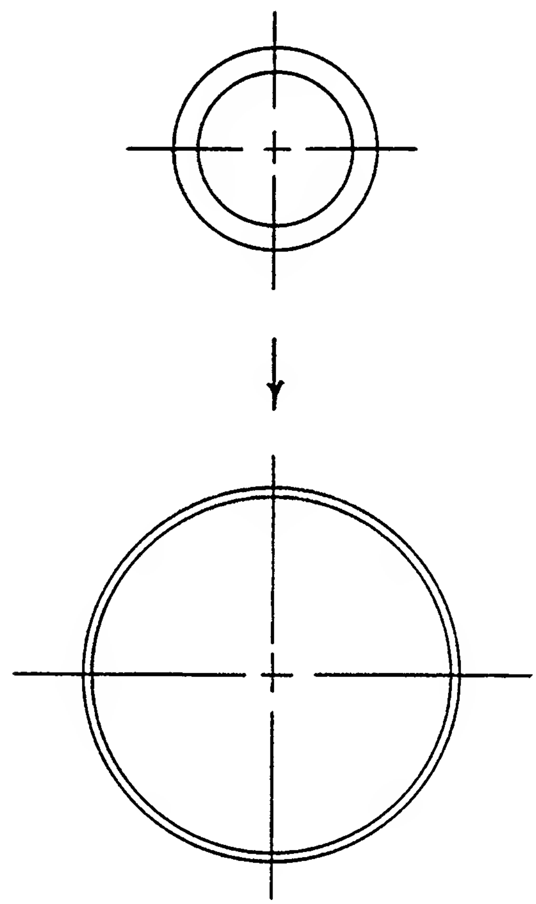
Here σ is stress; M is bending moment (force times distance); y is, as previously defined, the distance from the centroid to the point where the stress is being calculated; and I is the moment of inertia of the cross-sectional area. Thus the bigger is I, the smaller σ, everything else being the same (of course y also depends upon the type of cross-section chosen).

Similarly, the deflection at the end of the boom, δ, can (in this example) be calculated from

$$\delta = \frac{M\ell^2}{3EI}$$

where M is again bending moment and I is moment of inertia, while ℓ is the length of the boom. A large I gives less deflection. In this equation, E is a material property called the tensile modulus which measures the intrinsic stiffness of the material. Stainless steel, for example, has a tensile modulus (28×10^6 psi) almost three times that of aluminum (10×10^6 psi). Thus a given cross-section would be stiffer if made of stainless steel. However the stainless steel has a greater denstiy (0.28 lb/in^3) than the aluminum (0.1 lb/in^3), so stainless steel would weigh more.

We can also see that there are limits on how far we can locate the material from the boom centerline. Continuing to think of a circular tube cross-section, as we make the diameter larger, and the tube wall thinner,



the tube wall will have less and less resistance to local deflections, such as denting and dimpling. Such deformations, which can arise under either bending or compressive loads, are termed local buckling or crippling. Crippling constitutes failure for such a tube because it leads to a greatly decreased capacity to resist bending. You can illustrate this failure mode by rolling a sheet of paper into a tube and bending it (or once again using a soda straw). Thus designing a light-weight cross-section to resist bending loads involves a trade-off or compromise in which the moment of inertia, I, should be as large as possible consistent with resistance to crippling failures. If torsion (twisting) is present in addition to bending, the situation is complicated further.

The loads on the SSAA boom depend, among other things, upon the design of the scoop mounted on its end. In addition, wind loading of the boom is a possibility. At the time that the feasibility of alternative boom designs was being considered, the following design parameters for the various loads had been established.

Parameter	Value	Source
Axial digging (compressive) force	30 lb	test
Backhoe (tensile) force	20 lb	test
Shear digging (bending) force	4 1/2 lb	test
Wind load	130 fps extended 140 fps retracted	Mars Engineering Model

Instruction C

Devise a plan or method for comparing and evaluating alternative boom designs. The evaluation plan is to be intended as an aid in deciding which boom design concepts should be further explored and developed. It is not necessary to include numerical calculations (e.g., for strength or rigidity) in your evaluation plan; however you may want to include qualitative comparisons using some sort of ranking or weighting scale. Your evaluation plan should include those parameters you think are most important for the boom, whether or not they have been explicitly discussed in preceding portions of the case study.

When you have completed your evaluation plan, show it to your instructor for approval. After he or she has approved the plan, apply it (in your design notebook) to the boom designs discussed above and illustrated in Exhibits C-1 through C-4 and also to the designs you generated in response to Instructions A and B. Use the results of the evaluation to select one or more designs for further development.

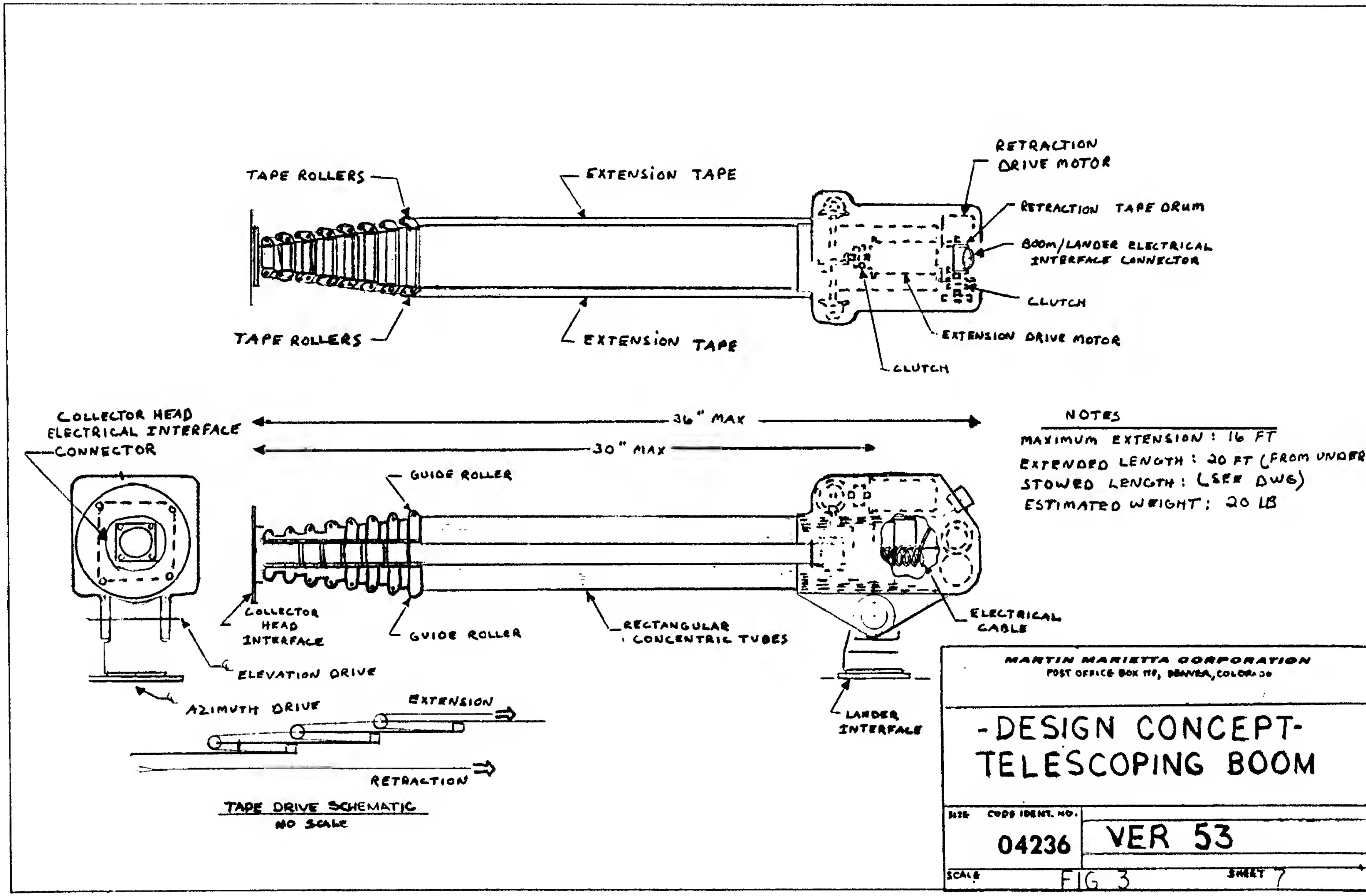


Exhibit C -1. Proposed Telescoping Boom Design.

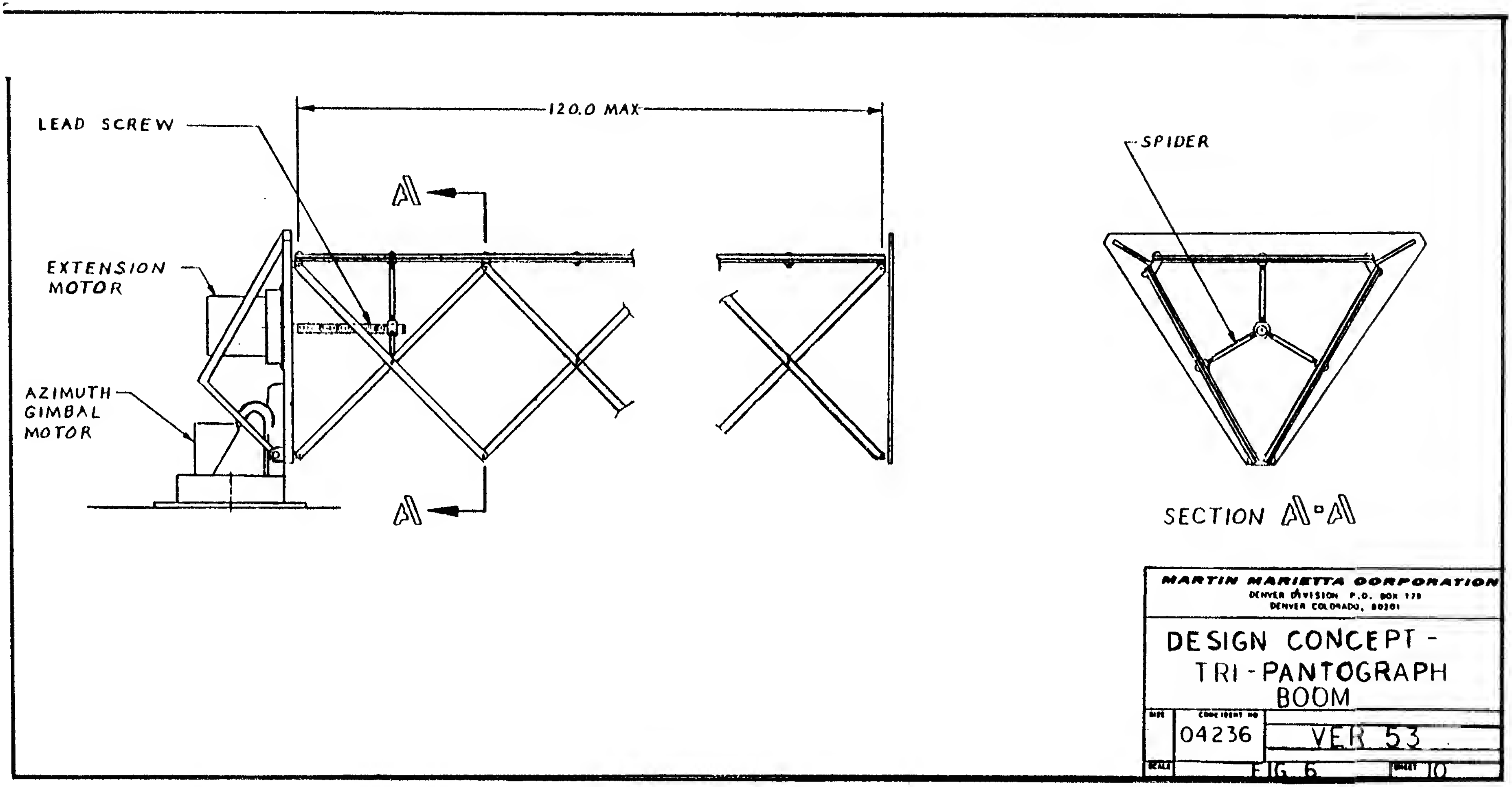
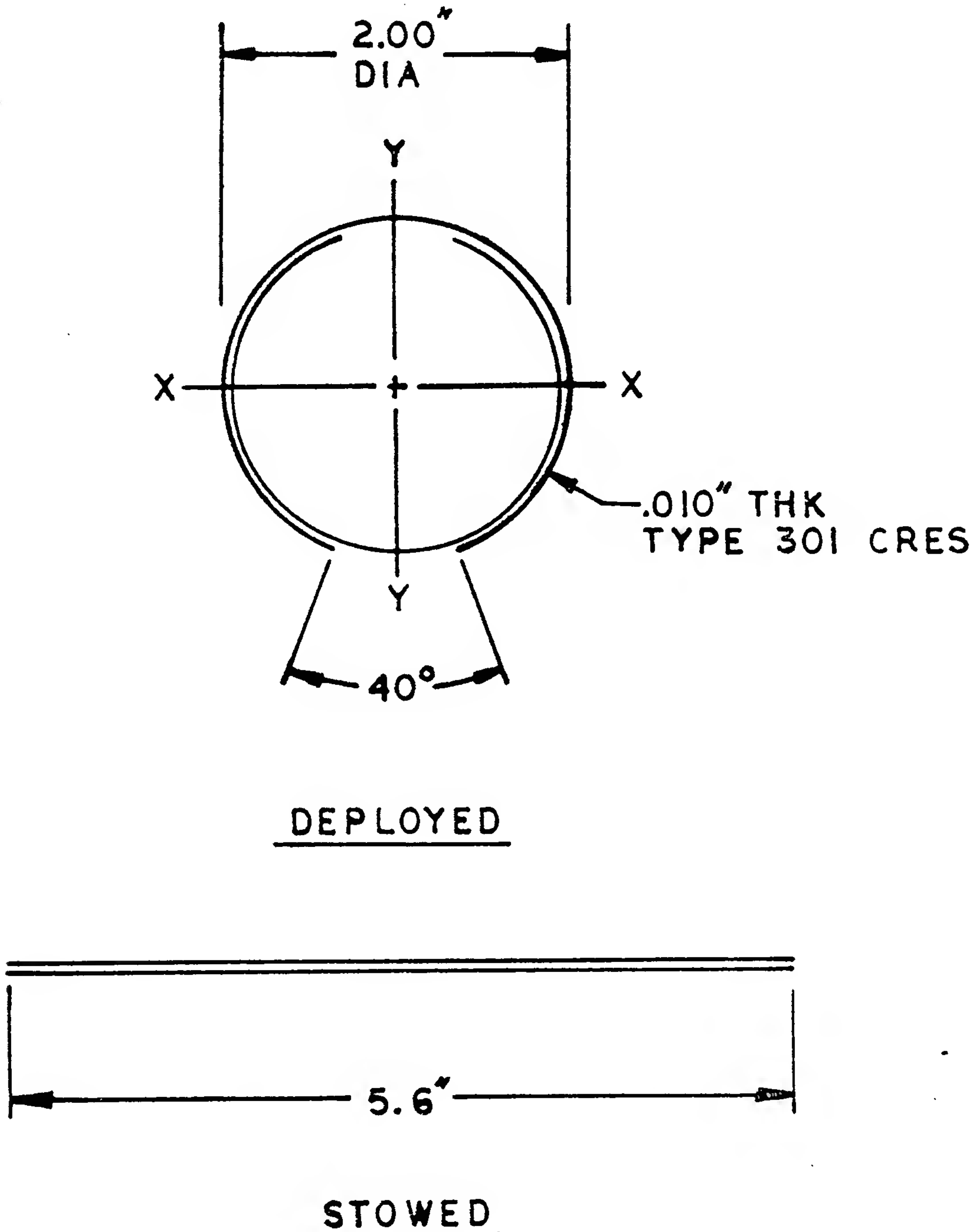


Exhibit C-2. Proposed Tri-Pantograph Boom.

Exhibit C -3. Cross-Section of Proposed Furlable Tube Boom.



SPAR 2" DIA. BI-STEM ELEMENT CROSS SECTION

FIGURE 9

SIZE	CODE IDENT NO.	
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SCALE	PAGE 12	SHEET

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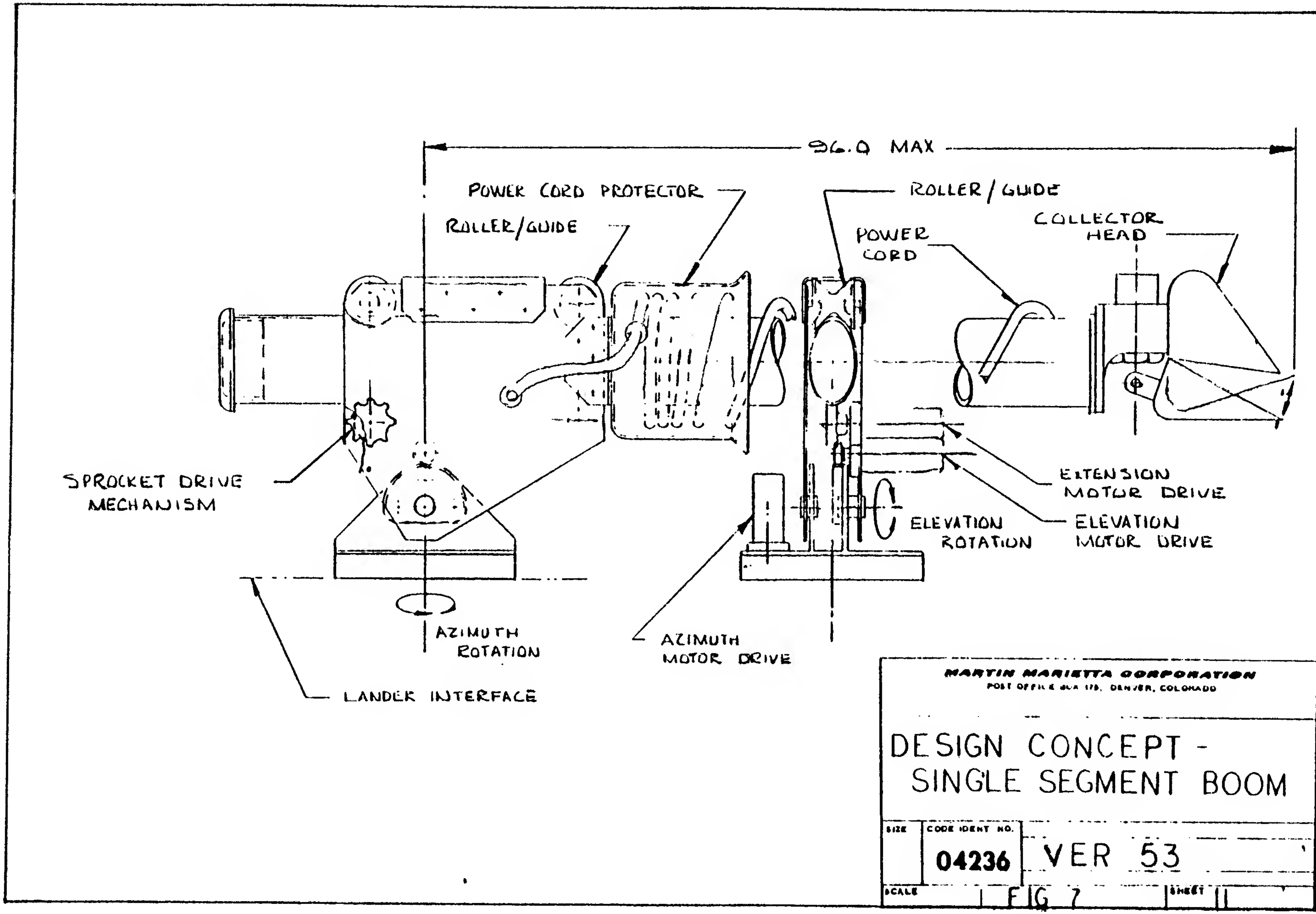


Exhibit C-4. Single Segment Boom Design.

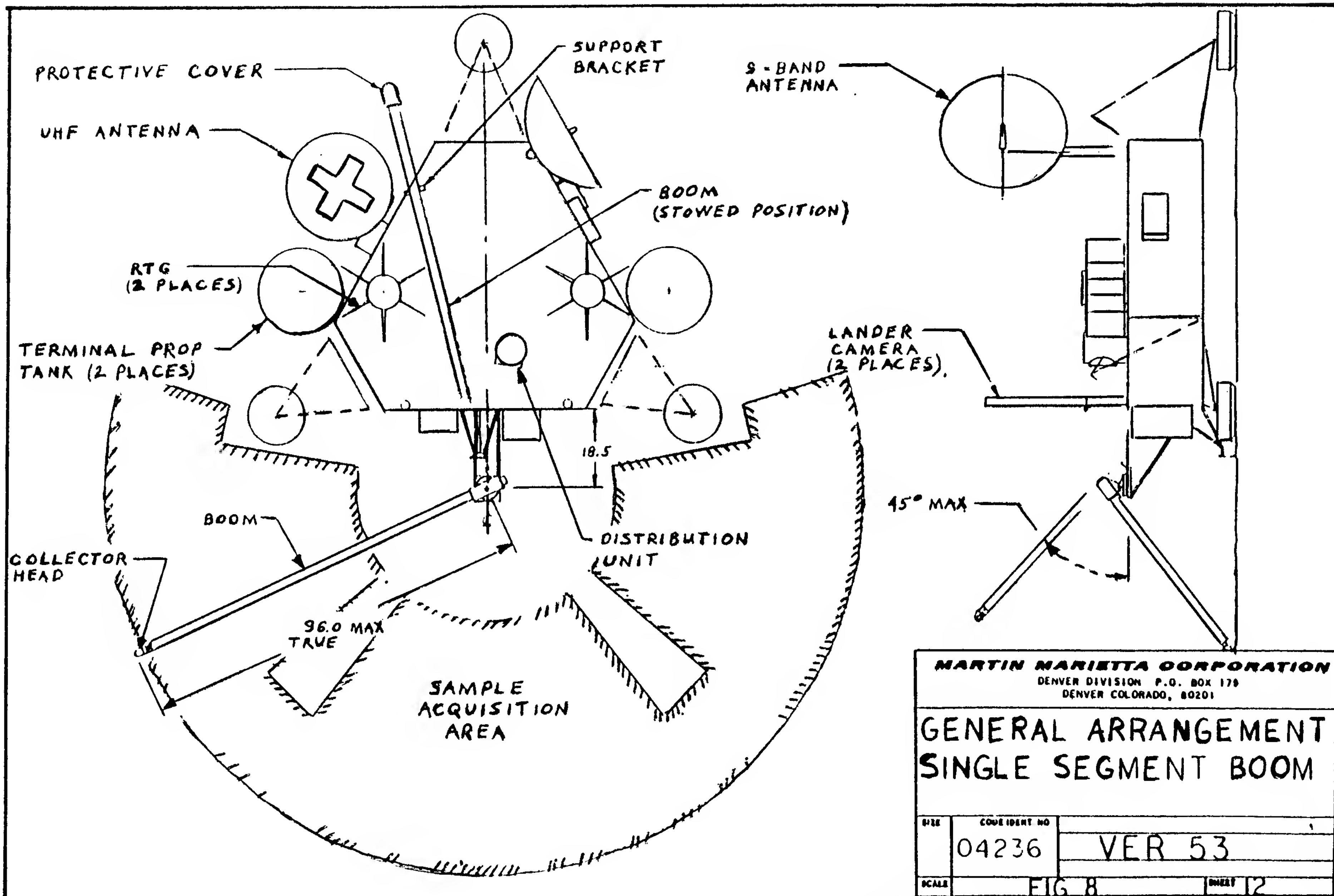


Exhibit C-5. Single Segment Boom Mounted on Lander Showing Sampling Area.

DIGGING INTO MARS (D)

The Viking surface sampler project team evaluated the four boom designs discussed in Section C as shown below:

COMPARATIVE RANKING OF BOOM CONCEPTS

	Telescoping Tape Driven	Furlable Tube	Tripanto-graph	Single Segment Tube
1. Maximum Rigidity/Strength	3	4	4	1
2. Minimum Weight	4	1	2	1
3. Maximum Reliability	6	2	4	1
4. Minimum Total Power	4	2	5	1
5. Minimum Cost	6	4	2	1
6. Minimum Integration Complexity	2	1	3	4
7. Minimum Profile - Wind Resistance	5	1	6	2
8. Maximum Sampling Area	4	2	5	6
9. Minimum Stowed Length	3	2	1	5
10. Minimum Control Requirements	1	1	1	2
11. Maximum Growth Potential (length)	2	1	4	5*
12. Minimum Stowed Volume	3	1	2	5**

Comparative Ranking: 1 = best design, 2 = second best design, 3 = etc.

*Maximum extension limited to 10 ft due to space restrictions.

**Deployed and stowed volume identical.

This table is slightly condensed from a report prepared in May 1970 entitled "A Comparison of Various Retractable Boom Design Concepts." Among the conclusions of that report were the following:

> The design criteria established for the boom is easily accommodated by a furlable tube-type boom. Comparison of the various extension concepts...revealed that the furlable tube boom is superior to all others with the possible exception of the Single Segment Tube.... This design concept possesses some inherent inadequacies, predominately with integration into

the VLS*, but the other performance parameters indicate that further consideration is warranted.

In summary, it is recommended that both the furlable tube and single element tube type booms be integrated into the Surface Sampler Elements Test Program.

Don Crouch recalled some of the general considerations that had gone into the boom selection: "We were really worried about the blowing dust on Mars, and the possibility that it might jam some of the moving parts of the boom assembly. This was one of the big problems with the pantograph design and with telescoping tubes--too many hinges, sliding joints and other places for the dust to get in."

Instruction D

As mentioned in Section C the Spar Bi-Stem furlable tube cross-section (Exhibit C -3) is only one of many cross-sections which could be used for a furlable tube boom. The Viking engineers had to compare and evaluate the various types of furlable booms before deciding on a final design.

Think of as many different furlable tube cross-sections as you can and show them in your design notebook. From these designs, choose several for further development, e.g. construction and testing of prototypes.

---

*Viking Lander System.

DIGGING INTO MARS (E)

Don Crouch said, "Many furlable antenna tubes are just part of a circle, perhaps overlapped.

Others use concentric tubes as in the Spar Bi-Stem designs. Some of the cross-sections are more complex.

"We were again worried about sand and dust getting into an open tube," he continued. "Several vendors proposed furlable tubes with closed cross-sections that seemed more suitable." One of these designs, suggested by Atlantic Research Corporation, Costa Mesa, California, appears in Exhibit E-1. This tube is made of two thin strips of maraging steel continuously welded along their edges. Maraging steels are a family of alloys which can be heat treated to very high strength levels. One of the advantages of this design is that a flat electrical cable can be led down its center to provide power and control functions for motors and solenoids on the collector head.

Another proposed boom was otherwise similar to Exhibit E-1 but instead of welding, a series of interlocking tabs were used to join the two halves of the tube. This design was eventually rejected after tests revealed that continued furling and unfurling caused some of the tabs to break off. Such a failure as a result of repeated loading or stressing is called fatigue failure. Don Crouch said, "We were also afraid that dust would filter in between the tabs."

Although the furlable tube boom had become the baseline concept, it was by no means clear at this time (1970) what all the parameters for the design should be. Among the parameters in question were tube diameter and wall thickness, as well as the type of cross-section. While alternatives were compared assuming a 10 ft boom length, this dimension was also subject to change. Both analytical and experimental studies were used in comparing various furlable tube designs.

The analytical work involved calculations of strength and deflection under various conditions and also of boom weight. In addition, the power required to furl and unfurl each boom was calculated. Exhibit E-2

shows how boom weight varies with tube diameter and cross-section. Of course the heavier tubes are stronger and more rigid. Calculated deflections as a result of wind loading on a 10 ft boom are shown in Exhibit E-3, with points of crippling failure by non-permanent buckling of the tube cross-section marked.

Later in 1970, when working prototype booms had been received from several vendors, a test program was set up at Martin Marietta to evaluate candidate designs. Several of these prototypes are shown in Exhibit E-4. Tests were performed to measure deflections in bending and in torsion, crippling loads, and natural frequencies. The natural frequency is the rate at which the boom will vibrate after being deflected and released.

It is common practice to prepare a test plan before embarking on such a program. The test plan outlines the procedures to be followed and helps to assure that the program is well-conceived and will yield useful results. Testing is often quite time consuming, thus expensive, so it is important to plan carefully to be sure of getting one's money's worth. Excerpts from the plan prepared for the boom testing program appear below.

3.0 TEST EQUIPMENT

a) 2, 4, and 6 lb weights
b) level
c) machinist's protractor
d) torque indicator
e) 50 ft steel tape
f) spring scale
g) 12 ft steel tape

4.0 TEST PROCEDURE

4.1 <u>Test Setup</u> - Mount boom solidly to bench with boom feeding out horizontally.

4.2 <u>Astro* Boom Test</u>

4.2.1 Extend boom 3 ft beyond last support.

1. Measure tip deflection from horizontal.
2. Measure force required to restore boom to horizontal.
3. Measure tip deflection with 2 lb weight applied to tip.
4. Measure tip deflection with 4 lb weight applied to tip.
5. Measure tip deflection with 6 lb weight applied to tip.

4.2.2 Extend boom 5 ft beyond last support.

1. Repeat 4.2.1-1 through 5.

---

*Vendor's name.

(4.2.3 - 4.2.6, repeat for 7.5 ft, 10 ft, 15 ft and maximum extensions.)

4.2.7 Record critical length of boom if crippling occurs prior to completion of 4.2.1 through 4.2.6. Record force required to restore boom to horizontal at critical length.

4.2.8 Retract boom to 15 ft extension.

1. Measure angular deflection with 10 in-oz torque applied to tip plate.
2. Measure angular deflection with 15 in-oz torque applied to tip plate.
3. Measure angular deflection with 20 in-oz torque applied to tip plate.

4.2.9 Retract boom to 10 ft extension.

1. Repeat 4.2.8-1 through 3.

4.2.10 Retract boom to 5 ft extension.

1. Repeat 4.2.8-1 through 3.

4.2.11 Rotate boom housing 90° about the boom centerline.

1. Repeat 4.2.1 through 4.2.7.

(4.3 - 4.5, repeat for other prototype booms.)

Typical results from this testing program are presented in Exhibit E-5. The plot compares torsional deflections (4.2.8, 9 and 10 above) for all four of the prototypes which were tested at this time.

In parallel with evaluation of the various boom designs, work was proceeding on the collector head. Several types of scoops were under consideration, and had to be evaluated. Furthermore, it was necessary to get information on digging forces to use for the boom analysis and testing program. This information (Section C) came from tests of prototype collector heads.

Exhibit E-6 shows the sort of collector head under consideration at this time. While a number of the details were subject to change, this illustration, incorporating a forward facing scoop ("lower jaw") plus backhoe is typical of the designs proposed. A solenoid opens or closes the lid, with a switch inside to signal when the scoop is full. After picking up a load of surface material, the lid can be closed and the boom retracted and rotated to position the collector head just above the intake for the appropriate experiment. Then the 180° rotation motor inverts the collector head and dumps the sample through the sieve into the intake. The backhoe is for digging trenches and piling up material, while several magnets are carried below the scoop.

Instruction E

Prepare a test plan for measuring the digging (compressive) and shear (bending) loads that would be exerted on the boom while scooping up soil. The test plan should make provision for two different collector head designs, each tested at angles of 0°, 15° and 30° to the boom, while the test soil should be lunar nominal. The beginning sections of the actual test plan written by the Martin Marietta engineers are quoted below.

SURFACE SAMPLER ELEMENT TEST PLAN

Fixed and Movable Jaw Collector Heads-Preliminary

1.0 TEST OBJECTIVES

The following represents the major objectives of these tests:

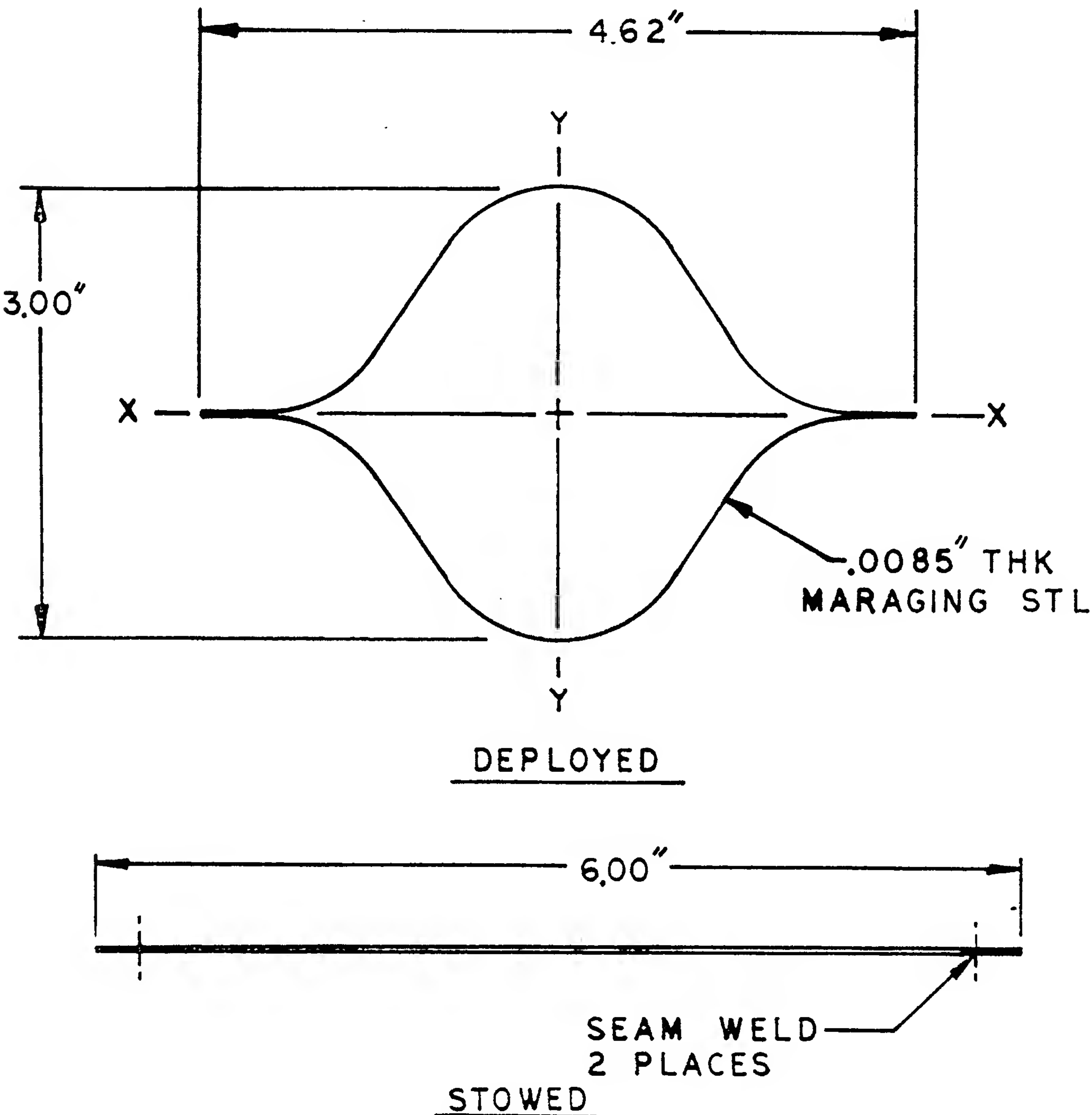
1. Determine forces required to fill the collector head at simulated distances of three (3) and ten (10) feet from the VLS.
2. Determine shear forces required to dislodge the acquired surface samples at the three and ten-foot distances.
3. Determine the effect of collector head angle upon the sample acquisition forces.
4. Record all general observations regarding the acquisition process.

2.0 TEST SPECIMENS

The "movable" and "fixed" jaw collector heads used for these tests are described in MMC Sketch Drawings SK837090602. Since these tests were concerned only with digging loads, the solenoid actuator of the movable jaw collector was disconnected and its upper lid was mechanically restrained to the maximum open position.

You should now complete this test plan.

Exhibit E-1. Cross-Section of Atlantic Research Corporation Furlable Tube Boom.



ATLANTIC BOOM ELEMENT CROSS SECTION

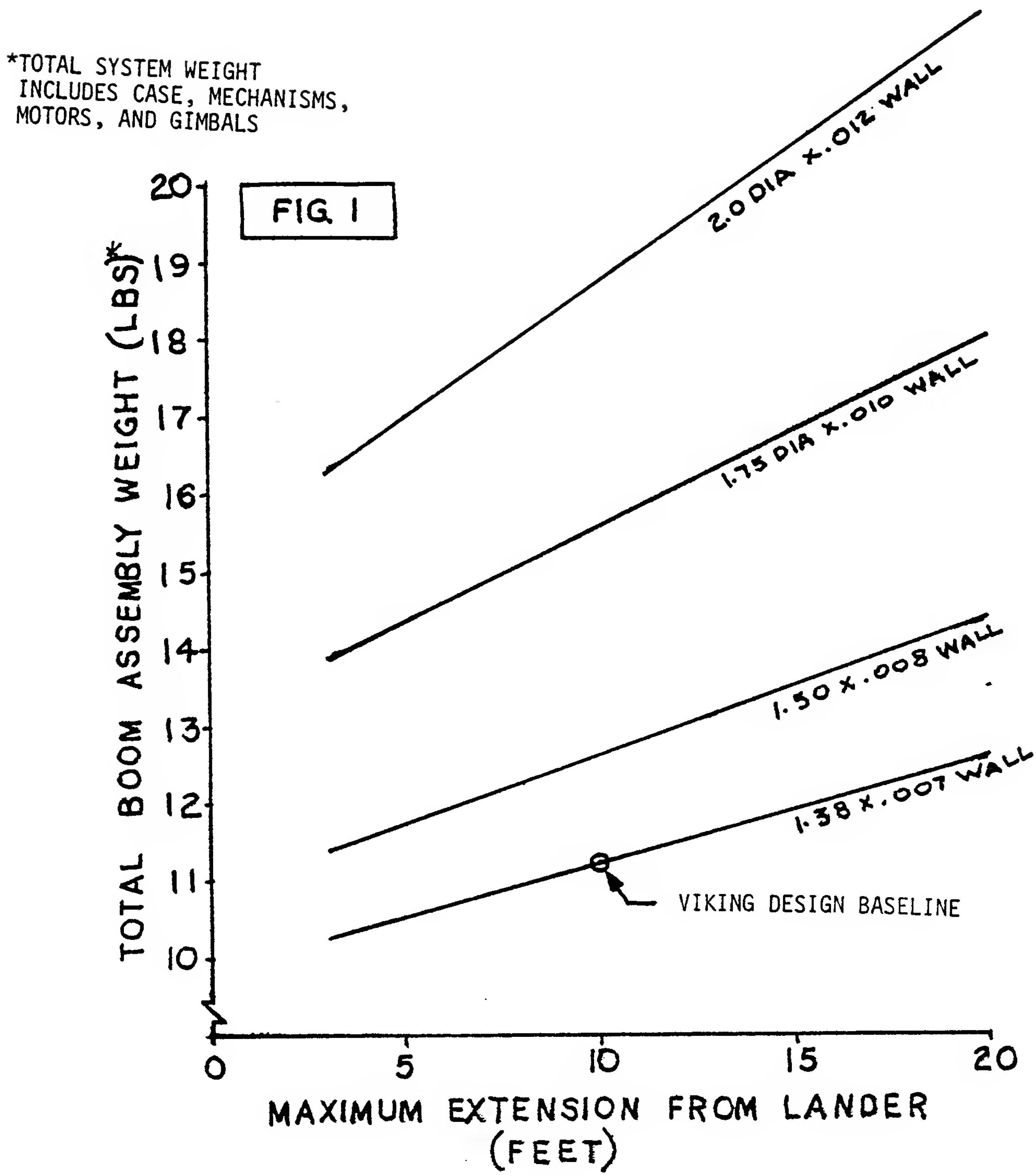
FIGURE 6

CHG	SIZE A	CODE IDENT NO. 04236	VER 60-5-1	
	SCALE	PAGE 10	SHEET	

Loomis 11/30/70

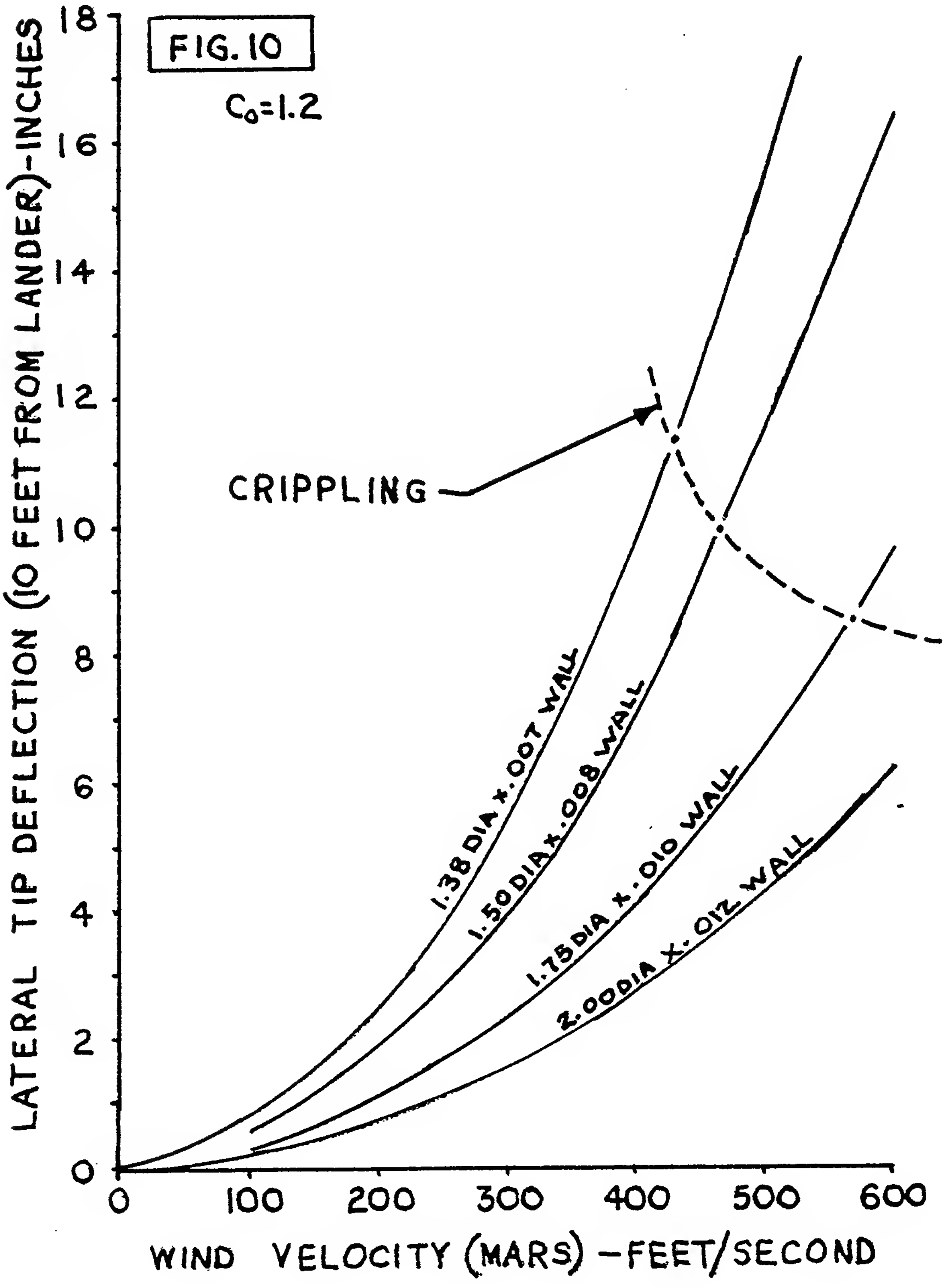
SURFACE SAMPLER
FURLABLE BOOM

Exhibit E-2. Parametric Study of Boom Weight.



SURFACE SAMPLER
FURLABLE BOOM

Exhibit E-3. Boom Deflections Under Wind Loading.



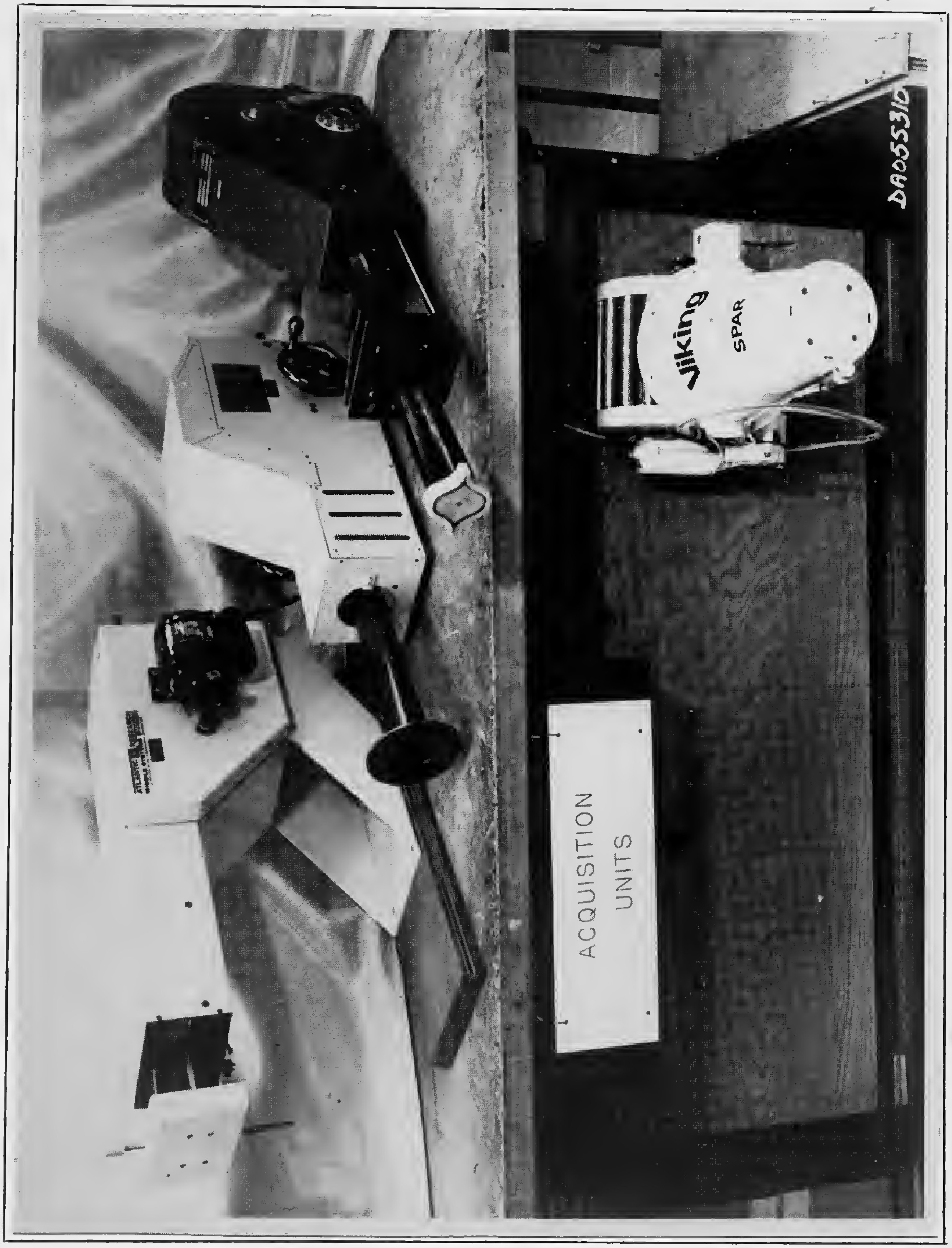


Exhibit E-4. Prototype Furlable Tube Booms Used for Laboratory Testing.

Exhibit E-5. Measured Torsional Deflections for Four Prototype Boom Designs.

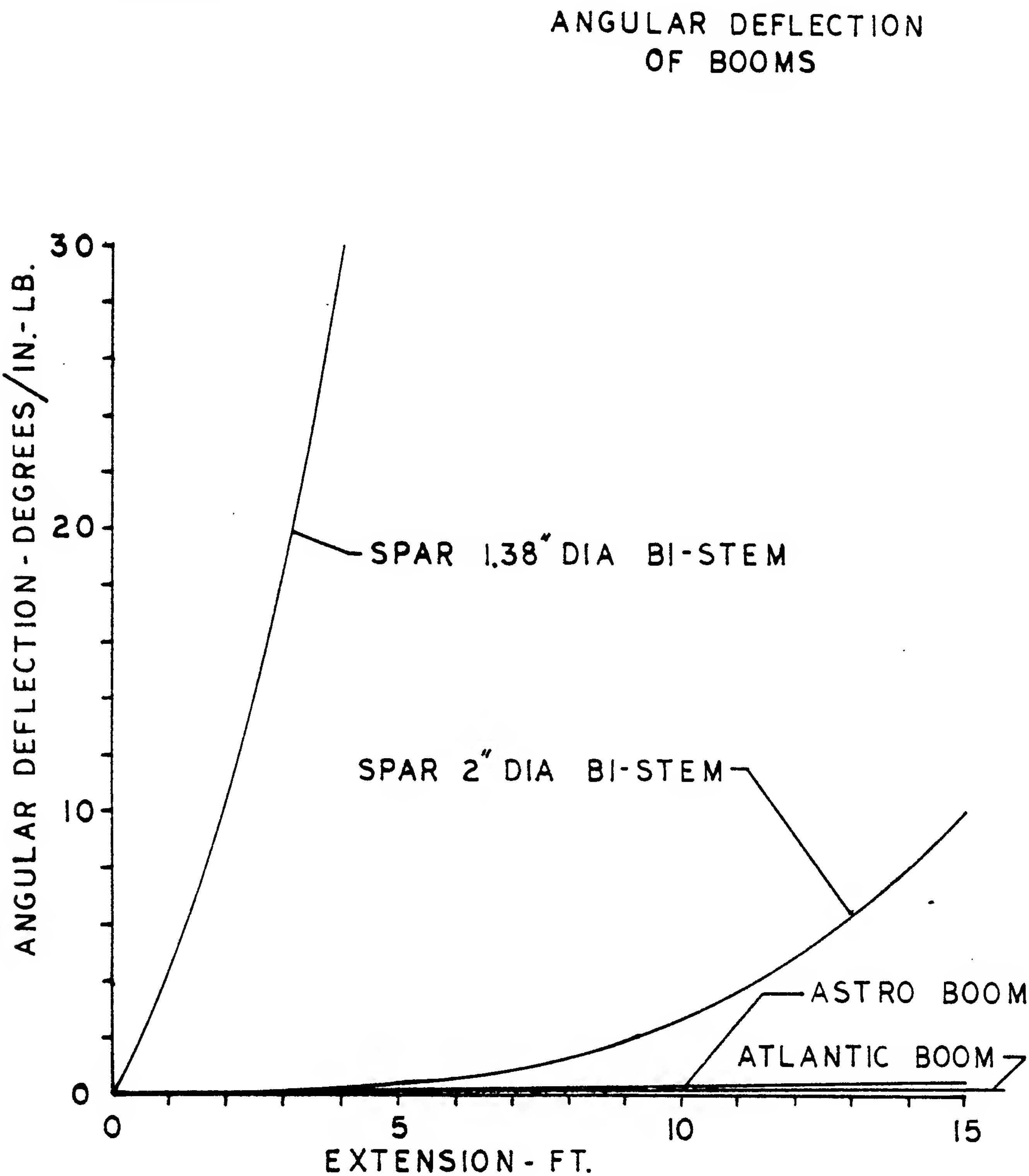


FIGURE 17

SIZE	CODE IDENT NO.	
A	04236	VER 60-5-1

J. Loomis 12/7/70 CHG SCALE PAGE 22 SHEET

Viking COLLECTOR HEAD

MARTIN MARIETTA
DENVER DIVISION

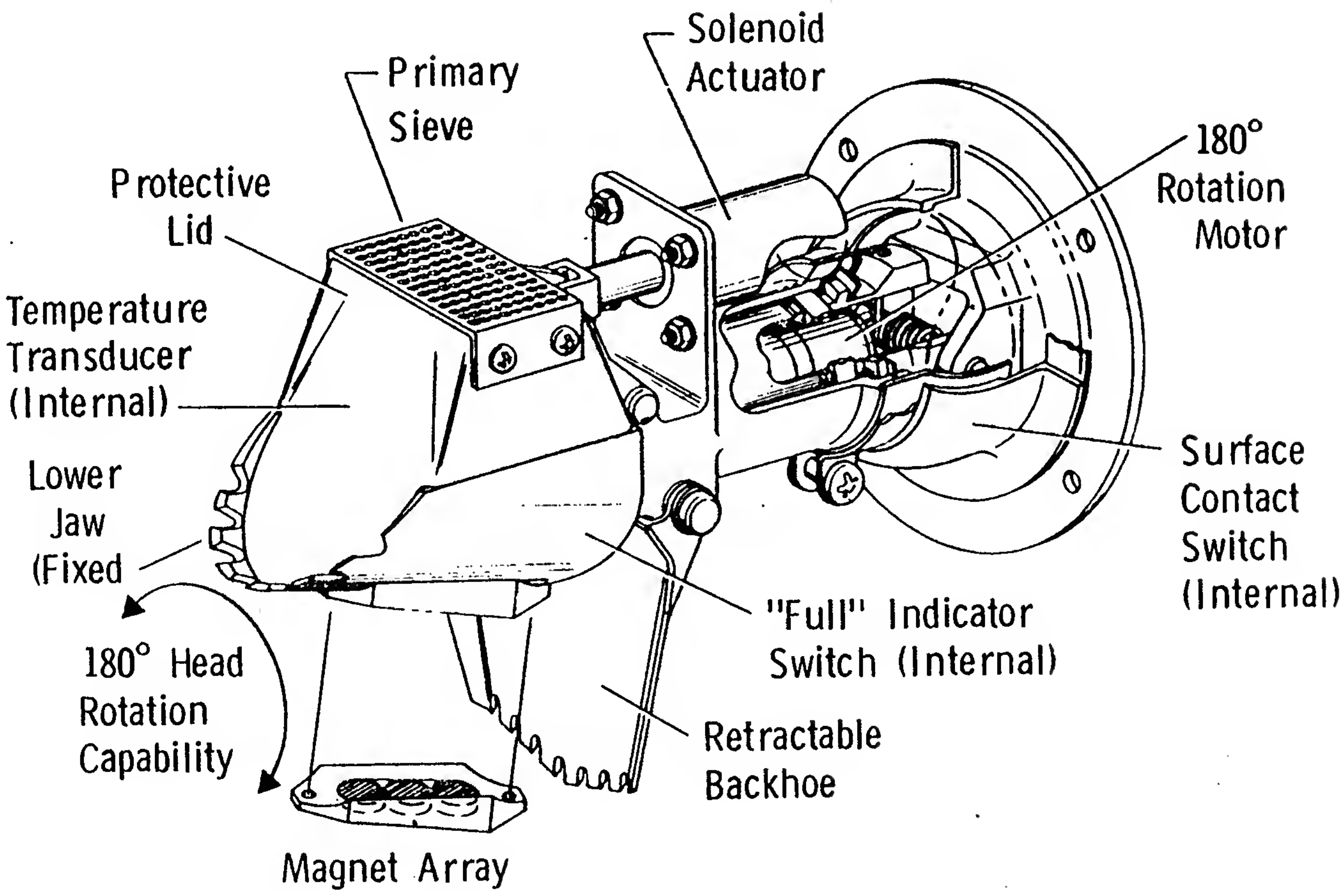


Exhibit E -6. Preliminary Collector Head Design.

DIGGING INTO MARS (F)

The actual test plan continued as follows:

3.0 TEST EQUIPMENT

1. Lunar Nominal Soil Model.
2. One (1)-inch diameter tube, 10 ft in length.
3. Balance Scales, 0-500 grams range.
4. Linear Spring Scales, 0-30 lb range.
5. Graduate Measuring Cylinder, 0-120 cc.

4.0 TEST PROCEDURE

4.1 <u>Test Setup</u> - Attach collector head (fixed or movable jaw) to tube boom. Collector head should be capable of pivoting such that its bottom can be rigidly fixed parallel to the boom (0°), or elevated upward at 15° or 30° above the boom major axis as shown in Figure 1.*

4.2 <u>Digging/Shear Force Measurements</u> - Perform the following sequences for both collector heads:

1. Adjust collector head angle to 0° and use scales to apply digging force parallel to boom at a simulated sampling distance of 3 ft. Record peak and average forces as collector head penetrates fully into soil.
2. With collector head still emplaced in soil model, reposition scales to measure shear force. Record peak and average forces as collector head shears soil sample. Record "Y" and "Z" distances.
3. Record shear force after soil sample is dislodged.
4. Remove soil sample from collector head and record its volume and weight.
5. Repeat (3) with empty collector head.
6. Repeat (1) through (5) two additional times.
7. Perform (1) through (6) for a horizontal distance of x = 10 ft.
8. Perform steps (1) through (7) for a collector head angle of 15°.
9. Perform steps (1) through (7) for a collector head angle of 30°.

A typical data sheet from these tests is reproduced as Exhibit F-2. Portions of the test report are quoted below.

---

*This figure is reproduced as Exhibit F-1.

The major points of significance which can be derived from the tests as shown on the data sheets follow:

* * *

3. The digging and shearing loads are well within those specified for the flight boom design (30 lb and 4 1/2 lb respectively at 10 ft). The shear loads, which have the lowest safety margin, are higher than 4 lb in some instances at a sampling distance of 3 ft, but are still within the specified capability of the boom.

6.0 CONCLUSIONS AND RECOMMENDATIONS

These tests verified that the sample acquisition digging and shear loads are well within the capability that was specified in the PD specification for the furlable tube boom. These preliminary tests should be expanded to include the loess, basaltic sand, and the lag gravel simulated Mars surface models as soon as they become available. Additional specific recommendations include the following:

* * *

3. Improve the technique of varying the soil compactness by characterizing with a penetrometer.
4. Improve the test set-up by mechanizing the collector head control and incorporating force and position transducers.

Don Crouch said, "Although the 10 ft furlable tube boom with a scoop-type collector head was our baseline design, there were many other possibilities still under consideration at this time (1970). For example, NASA said to us, 'What if we land on one big rock?' We were also very concerned about the reliability of the sampler, since if it failed the whole mission would be of little value. So we had programs going to look at hard-rock samplers and also at redundant samplers. We wanted to find out the best way of incorporating a second, back-up sampler to take over if the primary sampler failed. Also, there had been a lot of talk about extending the sampling range past 10 feet. There were several reasons for this. One was just the desire of the scientific community to have as big a sampling area as possible. Another was concern over the blast from the retro-rockets contaminating the soil around the lander."

As a result of these considerations, studies were undertaken by Don Crouch's group with the following objectives:

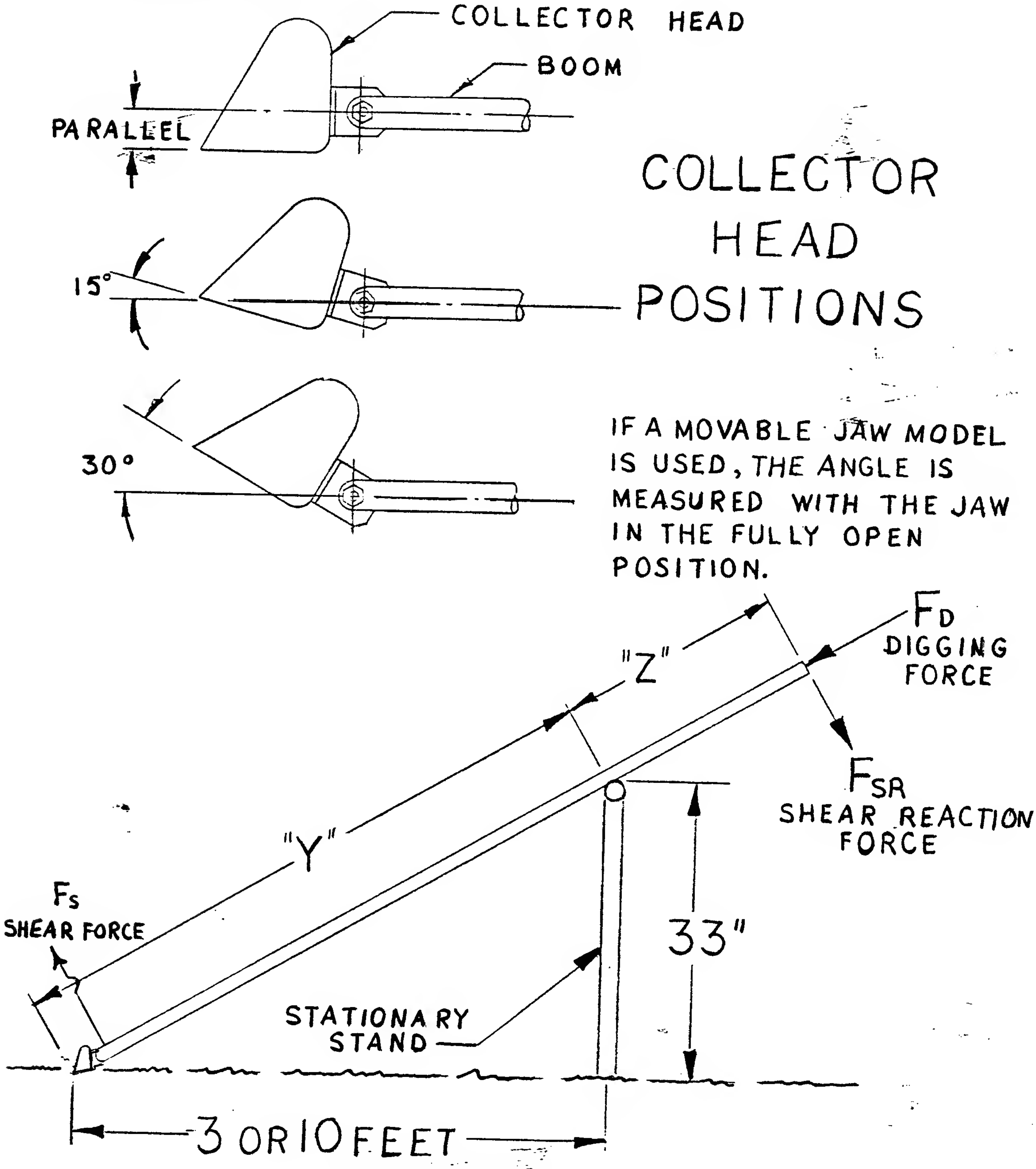
1. To investigate the feasibility of alternative samplers capable of retrieving samples from rock (aggressive samplers).
2. To examine methods for incorporating redundancy in the sampling system (adding a hard-rock sampler in addition to the boom and collector head would be one way of accomplishing this).
3. To develop means for acquiring samples beyond a 10 ft distance from the lander (recall that many of the boom design studies described in Feedback D included boom extensions of more than 10 ft; alternatively, a second, longer range sampling system in addition to the 10 ft boom could give redundancy as well as a wider sampling area).

Instruction F

Consider or reconsider in your design notebook ways of meeting the objectives listed above. You may wish to go back to ideas you had previously thought about, as well as generating new concepts based upon the added knowledge of the problem that you now have. Again strive for variety in your ideas and try to make sure that no class of possible solutions is overlooked. Use sketches and notes in this exploratory phase as before.

When you have exhausted the possible ways of meeting the three interrelated objectives given above, prepare a memorandum to your instructor in which you describe those you think worthy of further study, perhaps leading to developmental testing. For this purpose, imagine that your instructor plays the role of NASA's Viking Project Office. Your memorandum should briefly describe at least one but not more than three concepts for meeting each of the three objectives, with reasons for pursuing these particular alternatives.

Exhibit F-1. Test Set-Up for Measuring Digging Forces of Prototype Collector Heads.



URE-1. TEST SET-UP

Exhibit F-2. Data Sheet from Test of Prototype Collector Head.

DIGGING LOAD DATA SHEET

Test No. 2

Location UTF BLDG - CELL A-6 Lunar Drill Soil Model

Date 13 May 1970

Temperature 72 °F

Test Engineer D. S. Crouch

Humidity —

TEST CONDITIONS:

Collector Head Description: Moveable Jaw - Sk 837090601

Collector Head Angle (Rel. to Boom): 0°

Sampling Distance "X": 10 Feet

RUN DATA:

	*Run #1	**Run #2	***Run #3	
F_d (digging force) - max: (1)	$2\frac{1}{2}$	$5\frac{1}{4}$	6	lb.
(digging force) - av:	—	—	—	lb.
F_s (shear force) - max: } Measured at Collector Head Perpendicular to Boom	$\frac{3}{4}$	$3\frac{1}{2}$	4	lb.
(shear force) - av:	—	—	—	lb.
Distance "Y"	—	—	—	in.
Distance "Z"	—	—	—	in.
F_{sf} (shear force) soil sample dislodged	—	—	—	lb.
F_{se} (shear force) collector head empty	—	—	—	lb.
Sample Volume (2)	65	54	87	cc.
Sample Weight	87	75	125	gr.
Calculated Bulk Density	1.34	1.39	1.44	gr/cc

TEST COMMENTS:

* Loose Soil - No Compaction

** Light Compaction

*** Medium Compaction

(1) At lower digging angles (Sampling @ 10 Feet) Penetration of Upper Collector Lid is minimized or eliminated thus reducing Digging Loads Below that of Test No. 1

(2) Sample Collection Satisfactory

DIGGING INTO MARS (G)

In the course of studying alternate and redundant samplers, the Viking engineers classified possible types of samplers into three groups:

- -- bulk particulate samplers
- -- selective particulate samplers
- -- hard-rock samplers

A table was constructed in which samplers of each type were listed and compared. This table appears as Exhibit G-1.

Simple tests were conducted on most of the concepts listed in Exhibit G-1. For instance, several types of rotary abraders were tried on pieces of firebrick or rock. Similar tests were conducted on a rotary-percussion drill. This consisted of a tungsten-carbide bit enclosed within a tubular casing. The bit was driven at 1600 rpm and subject ot 16,500 percussive blows per minute, each blow having an energy of 0.72 in-lb. This design was rated as the most nearly universal--i.e., one capable of sampling from almost any potential surface condition.

Several possible locations for mounting the various alternative or redundant samplers were considered. The rotary percussive drill and the other aggressive samplers were envisioned as mounted at the end of the meteorology boom. A rock drill directly mounted to the frame of the lander was also discussed. This would give much higher drilling forces.

However, after these preliminary studies had been completed, NASA decided that the probability of encountering hard-rock conditions was low, and work on most of the aggressive samplers was stopped. Don Crouch pointed out an additional reason for this decision. "The biologists said that if we landed on a rock there wouldn't be any bugs anyway."

Because the lander-mounted rotary percussive drill was considered a universal sampler, not restricted to rock, work on this alternative continued. A breadboard model--one using available components where possible--was designed, built, and tested over the next few months.

Then, during 1970, the schedule for the Viking launches was slipped from 1973 to 1975. Don Crouch explained the reasons for the schedule change: "NASA was having some budget problems, and in addition there was the technical risk involved in trying to get Viking and its relatively complicated science instruments developed by 1973. In retrospect, the schedule change was a good decision."

"From our standpoint, it relieved some of the pressure, and gave us a bit of breathing room," Don continued. "We were able to take the time to examine several of our ideas in more detail."

In addition to the rotary percussive drill discussed above, the alternate sampling methods chosen at this time for detailed study included the following:

-- passive collector to catch wind-blown dust
-- mortar-launched, dragline retrieved sampler
-- remote-controlled roving sampler

Methods for moving the entire lander over the Mars surface--perhaps as much as several hundred feet from its landing site--were also studied. Work continued on all of these alternatives during 1971, culminating in tests of breadboarded prototypes for all except the mobile lander.

Instruction G

Pick <u>one</u> of the four alternative samplers:

1. rotary percussive drill,
2. wind-blown dust collector,
3. mortar-launched sampler,
4. rover,

and prepare a preliminary design including whatever features you would want in a prototype for test purposes. Your design does not need to include specifications for purchased parts such as electric motors--simply indicating where the motors would be located in the prototype will suffice. Likewise, you do not need to go into such aspects as control electronics. However your design should include all of the main conceptual features so that it could easily be extended to a set of working drawings from which a prototype could built and tested. The purpose of such tests would be to demonstrate--in the laboratory--"proof-of-principle." This means finding out whether or not the basic idea will work. Thus specific features or details which are not necessary for demonstrating proof-of-principle may be omitted. Prototypes such as the boom units shown in Exhibit E-4 can be considered proof-of-principle models.

You should work out your design in your notebook and then present the final version as either a set of carefully executed freehand sketches, or, preferably, a set of layout drawings made to scale using drawing instruments. Be sure to pick a large enough scale (full, if possible) so that your drawings are easily read and understood. To aid you in carrying out this instruction, some of the design objectives established by the Viking engineers for each of the four alternatives are given below. These objectives are quoted or paraphrased from actual

Viking project documents, but do not necessarily include all relevant design requirements for the particular system. For example, electric power requirements were specified for the rotary drill but not the rover.

Rotary-Percussive Drill

-- capable of sampling any of the five surface models (lunar nominal, dune sand, loess, lag gravel, exposed rock)
-- sample volume 7 - 10 cc
-- required to acquire only one sample
-- capable of delivering sample directly to scientific experiments
-- minimum weight and power consumption: weight less than 10 lb; peak power not to exceed 200 watts; power consumption less than 10 watt-hours

Wind-Blown Dust Collector

-- passive (no moving parts)
-- capable of collecting dust particles in size range of 0 - 1000 μm
-- deliver by gravity to scientific experiments (electric vibrators may be used to aid flow)
-- omnidirectional; capable of collecting dust regardless of wind direction
-- maximum diameter of 8 in. to be compatible with packaging of scientific experiments
-- may be one-shot deployable to conserve space

Mortar-Launched Sampler

-- weight - less than 10 lb
-- launch range - minimum of 100 ft (30.5 m)
-- repeatability - eight (8) launch and retrieval cycles
-- sample recovery - twenty (20) cc per cycle
-- dragline retrieval rate - approximately 1 ft/sec; dragline tension limiter
-- aiming capability - elevation and azimuth through 40°
-- propellant - non-contaminating, repeatable
-- control system - fully automated

Rover

-- able to serve as a back-up sampler (capable of acquiring only one sample), or, alternatively, as the primary sampling system (multiple sampling capability).

-- rover to carry either a scoop or a rotary drill*
-- power, control, and communications to be provided by existing lander systems through cable to eliminate electronics and thermal control on the rover
-- sampling traverses will take a path which keeps the rover in view of the lander at all times. Rover navigation to be provided by using the lander imagery displays to select and define a safe path.
-- capability of obtaining samples from the specified models of lunar nominal, dune sand, lag gravel and loess
-- maximum system weight of 20 lb
-- range from 50 to 300 ft (assuming rover in lander view)
-- capable of obtaining surface samples having a volume of 10 cc

*For purposes of your design, do not go into detail on these.

TABLE 1. POTENTIAL SURFACE SAMPLER CONCEPTS APPLICABLE TO THE VLS.

SAMPLER TYPE	MAJOR ADVANTAGES	MAJOR DISADVANTAGES
Bulk Particulate		
-- Boom deployed scoop or backhoe	-- Multiple site selectivity -- Homogeneous sample	-- Limited to particulate/gravel surfaces
-- Non-rotating tubular collector	-- Simplicity -- Homogeneous sample	-- Limited to particulate surfaces
Selective Particulate		
-- Rotating helical conveyor	-- Simplicity	-- Non-homogeneous sample -- Subject to jamming
-- Rotating brush/scoop combination	-- Increased compacted/cemented soil sampling capability	-- Difficult to integrate with existing system
-- Vacuum collectors	-- Increased soil model sampling capability, i.e. thin as well as thick layers of particulate overburden	-- Non-homogeneous sample -- Marginal operation in minimum Mars atmosphere
-- Aerosol collectors	-- Same as vacuum collectors	-- Same as vacuum collectors -- Requires additional power source (i.e., stored gas)
Hard Rock		
-- Rotary-percussive drill	-- Applicable to all surface models	-- Some sample particle sorting
-- Rotary drill	-- Applicable to all surface models	-- Some sample particle sorting -- Relatively high drilling thrust req'd -- Sample heating
-- Abraders/scoop combinations	-- Applicable to many rock models	-- Difficult to integrate with existing system -- Sample heating
-- Chippers/scoop combinations	-- Applicable to many rock models	-- Difficult to integrate with existing system

Exhibit G-1. Table of Alternative Surface Sampler Design Concepts (Retyped from Original).

DIGGING INTO MARS (H)

Work of the Viking engineers on the four alternate samplers is summarized below.

Rotary-Percussive Drill

Based upon the results of the tests mentioned in Section G, a breadboarded prototype drill to be deployed over the side of the Viking lander was designed and fabricated. The drill, shown in Exhibit H-1, incorporated a rotary impactor similar to those used in impact wrenches. Material cut by the 3/8 in. drill bit is carried up the stationary auger tube to the sample shuttle. The shuttle is then pulled by a cable to the science experiments where the sample is dumped by gravity into the appropriate opening. This is a "one-shot" design capable of delivering only a single sample. Weight and power consumption for the proof-of-principle drill sampler were given as follows:

power head w/drill string	1.5 lb
feed mechanism	0.4 lb
sample transport w/motor	1.0 lb
housing	0.7 lb
Total	3.6 lb

power head: 28 VDC x 1.3 amp x 5 minutes = 182 watt-min
feed motor: 28 VDC x 0.1 amp x 5 minutes = 14 watt-min
transporter: 28 VDC x 0.5 amp x 2 minutes = 28 watt-min

Tests of the drill using the various Mars surface models showed the penetration rate to be slow in rock, with large temperature rises (60 - 75°F) and rapid dulling of the drill bit. However performance was generally acceptable in the other surface models. Based upon the tests, a set of preliminary design specifications for a flight model drill sampler was prepared.

A reliability study was also begun to determine the improvement that might be expected from including a drill sampler along with the baseline boom and collector head. Using a reliability (probability of successful operation) of 0.9998 for the drill sampler, the plot in Exhibit H-2 was obtained. This plot applies to the biology experiment only.

A portion of the recommendations stemming from this study read as follows:

> ...it is recommended that the back-up drill sampler effort be continued to improve its performance and to develop a prototype of the controls for the unit. The controls prototype can be a breadboard system, also made from off-the-shelf

components, to determine any unforseen problems in the remote operation of the sampler. Further, it is recommended that additional effort be expended in the improvement of the shuttle transport...

Wind-Blown Dust Collector

More than two dozen conceptual designs for passive dust collectors were generated. From these, nine were selected for a testing program. Prototypes of the nine were fabricated and tested in a dust storm simulation chamber. All were attachments fitted to the top of an 8 in. diameter, 30° funnel. The attachments included several types of vanes and baffles, as well as a honeycomb insert and a double-funnel. A design using a louvered rim is shown ready for testing in the dust chamber in Exhibit H-3.

The dust chamber was specially built for this series of tests and used a fan to blow dust fed from a vibrating hopper across the test model. The dust was made by grinding rock to a 0 - 1000 μm particle size range. This was a comparative test in that all designs experienced the same conditions, which were not, however, a close simulation of conditions on Mars (because of the differences in gravitation, atmospheric density, etc.).

Using the dust chamber, the nine prototype collectors were compared to a funnel without attachments. All were found to perform about the same as the bare funnel. Six collectors, including the bare funnel, were then field tested outdoors.

A basic conclusion of the passive collector study was, "...all of the design concepts tested will passively collect nearly equivalent quantities of particulate samples...". It was felt that a passive collector could, over a long enough time period, deliver enough material so that the science experiments could be carried out. A design approach for a passive collector which would add 1 1/2 to 2 lb to the lander weight was suggested.

Mortar-Launched Sampler*

The breadboarded mortar-launched sampler used a hollow projectile as the sample collector. This projectile-collector consisted of a tube closed at the front by a blunt nose. After being launched by the mortar the collector would be pulled back to the lander by a dragline,

*This portion of the surface sampler design effort is discussed in more detail in another case study: "DIGGING INTO MARS II: Feasibility Study of a Mortar-Launched Surface Sampler."

the open end of the tube scooping up surface material until full. The prototype is pictured in Exhibit H-4 with the collector ready for insertion into the barrel of the mortar.

In the conceptual design stage, a number of different ways of launching the projectile-collector were considered. Eventually a compressed gas system using CO_2 was chosen. The gas bottle can be seen in Exhibit H-4. A quick-release valve admits a small amount of 900 psi CO_2 to the mortar, launching the projectile-collector. The collector is retrieved by pulling in the dragline--30 lb test fishing line--with a modified fishing reel. The collector is pulled back into the launch tube, where the sample is dumped by gravity to the science experiments.

The prototype launcher was fired more than 100 times during the testing program. The average range of the projectile was 150 ft, the gas consumption 1 gm/shot, and the average sample picked up by the collector 12 cc. The Conclusions and Recommendations section of the report on the mortar-launched sampler included the following statements:

> The mortar-launched surface sampler concept that was designed, fabricated, and tested under this study is a feasible backup system to the primary Viking surface sampling system.
>
> It is recommended that a more advanced flight-prototype mortar system be developed to meet the following preliminary specifications...
>
> It is estimated that a reliable, efficient prototype of flight hardware configuration can be developed within six months after go-ahead.

Estimated weight of the flight model mortar was 8.0 lb.

Rover

A drawing of one of several designs for a rover (also called an extended surface sampler or ESS) is shown in Exhibit H-5. This rover carries a drill-type sampler similar to the rotary-percussive drill discussed previously. Studies indicated that the primary difference between a one-shot rover and a design capable of multiple sampling would be the need in the latter case for a system to retrieve the control cable.

The table below describes some of the features of the rover or ESS design.

Subsystem	Description
Mobility	Chassis articulated in roll. 4 rigid metal wheels (12 in. diameter, 2 in. wide) with grousers. Each wheel independently powered by 1.5 watt DC planetary gearmotor. Scuff steering Nominal speed, 3.9 ft/min. Step climbing ability, 5 in.
Control	Logic on lander controls ESS stepper switch to provide desired mobility function or sampling. Proportional control of mobility based on initial locomotion and turning calibration.
Cable	4 wires, #26 gage, TFE wrap or polyimide wrap insulation.
Cable Management	Desirable for multiple sortie system. Motor driven drum actively pays out and retrieves cable. Provides traction assist for ESS return to lander.

Scuff steering means driving the wheels on opposite sides of the rover in opposite directions. The peak power demand of the rover (exclusive of the sampling system) would be 6 watts, with an energy consumption of 1.54 watt-min/ft. Considerable attention was given to control; in contrast to the other back-up samplers, the rover had more complex control requirements.

A proof-of-principle prototype rover was built and tested. The primary objectives of the test were to investigate scuff steering performance on simulated Mars surfaces, as well as other mobility characteristics such as climbing ability. Operation of the prototype was generally satisfactory.

As a result of the work outlined above, preliminary specifications for a flight-model rover were prepared. These included the target weights listed below:

mobile unit	10.5 lb	
chassis (3.5 lb)		
wheels (2 lb)		
drivemotors (2 lb)		
stepper switch (1.5 lb)		
sampler assembly (1.5 lb)		
deployment and stowage	5.5	
cable	1.0	(0.5 each additional 50 ft)
cable management	2.3	
contamination control seals	0.2	
electronics	0.5	
	20.0 lb	

Among the conclusions and recommendations of the rover study were the following.

> The probability of obtaining one sample and the probability of obtaining the total number of samples desired...will be greatly improved by employing the ESS concept...it is recommended that the ESS be seriously considered for inclusion on the lander...A prototype flight unit should be fabricated ...The controls prototype can be a breadboard system employing off-the-shelf components to determine any unforseen problems in the remote operation of the ESS.

At about the time the studies above were being completed--mid-1971--the surface sampler subsystem was undergoing the first of a series of design reviews. The purpose of a review is to subject the proposed design to the scrutiny of a group of people not directly involved with it. Hopefully, their different perspective and lack of personal commitment will provide fresh insights and suggestions for the designers, perhaps helping to locate potential problem areas.

Design reviews are common in many industries. Typically, the engineering team makes a presentation using a variety of visual aids--and sometimes actual pieces of hardware. It is often not too far wrong to think of the engineers as trying to sell their design to a perhaps somewhat critical group of buyers--in this case NASA personnel, outside consultants, and representatives of the various science teams. Considering the whole Viking project, there were a large number of reviews--several at various stages in the development of each major system, and some for the entire mission. Don Crouch described the

usual procedure. "These design reviews are required by contract. The first is a Preliminary Design Review. This takes place when we've gone through all the options and alternatives--when the engineers have had a chance to 'do their thing.' We'll present the results of our tests on engineering evaluation models--the breadboarded prototypes--and make recommendations for further work."

"There would be about 75 people at the reviews--engineers from Langley, contract managers, the science community. It's a 2 or 3 day event. Frankly, I shudder to think of them."

"At the end, we agree--or disagree--on what to do next--whether to go on as planned, try other alternatives--what the general direction should be. After the Preliminary Design Review, the next stage is to design the flight hardware."

At the Preliminary Design Review (PDR) for the surface sampler subsystem--held in April 1971--the then-current status of the baseline SSAA with furlable tube boom was described in considerable detail. At that time, four different types of furlable tubes were still being considered: Spar Bi-Stem (Exhibit C-3), welded tube (Exhibit E-1), tab-locked tube (otherwise similar to Exhibit E-1), and a design which would roll up as a single ribbon but spiral to a circular tube shape when deployed.

The control system for the boom has not been discussed thus far. At the PDR it was described as follows:

> Potentiometers are mechanically coupled to all three degrees-of-freedom axes thus providing an electrical analog position signal for use in the closed loop servo control system. Limit switches are provided in all axes to preclude mechanical damage in the event of inadvertent overtravel. Overload switches are provided to protect the boom in case it is inadvertently powered into an obstacle. The switches will provide a shutdown signal which will terminate all operations until a ground command update is transmitted.

"Closed loop servo control" refers to a common feedback control system. Electric motors drive the boom in and out, as well as rotating the gimballed mount about horizontal (elevation) and vertical (azimuthal) axes. By operating a motor for a given time interval, it would be possible to estimate the resulting position of the collector head, thus achieving a crude means of control. After several boom movements, however, there would be considerable uncertainty about its final position. Such a control system would be called an open loop.

system; in this example it is something like navigating a ship by dead reckoning. Closed loop or feedback control can be provided by using transducers--in this case rotary potentiometers--to indicate at all times where the collector head is (thus "closing the loop"). A rotary potentiometer is simply a variable resistor, here incorporated in an electrical circuit so that the voltage across the potentiometer is proportional to the angular position of the shaft. Thus the azimuthal and elevational coordinates of the boom are given directly by voltage signals from the corresponding potentiometers. Likewise, the boom extend/retract potentiometer is geared to the boom sprocket drive system. These voltages serve as feedback signals to the control electronics and allow the collector head to be positioned within less than an inch of the commanded position under most conditions.

The collector head design at the time of the PDR was as previously shown in Exhibit E-6. With the collector head inverted to dump a sample, the lid solenoid (Exhibit E-6) would be vibrated at 6 to 10 Hz to aid the flow of material through the sieve. Other aspects of the collector head dealt with at the PDR included worst case operating conditions such as bearing friction. For example, the 180° rotation motor (Exhibit E-6) was to have a stall torque of 150 in-oz, while the maximum bearing friction was estimated to be 40 in-oz. Thus the design margin was 150/40 or 3.75.

Weight estimates at the time of the PDR were as follows:

Component	Current Estimate(lb)	Allocated(lb)
acquisition assembly		
boom	12.0	
collector head	2.2	
collector head shroud	0.5	
processor/distributor	9.0	
mechanical subtotal	(23.7)	(16.1)
controls assembly	(11.0)	(8.0)
magnet array	(0.3)	(0.3)

Possible weight reduction schemes were presented.

Considerable attention was also given to cleaning and sterilization procedures and to the avoidance of organic materials. Other topics at the PDR included the reliability of the surface sampler, plans for further testing, manufacturing considerations, and scheduling of the remaining work. The status of the four backup or alternate surface samplers discussed in the first part of this Feedback was also described.

Instruction H

Decision making is an important aspect of design, and of engineering in general. Many critical decisions must be made during a complex project such as Viking. One of these is now at hand: what should the final surface sampler design be? Should the baseline 10 ft furlable tube boom be retained, modified, supplemented, or replaced? If retained or modified (for example by lengthening the boom), should a backup sampler be added for redundancy? If so, which backup sampler should be selected? If replaced, what should the replacement be?

It is now up to you to make the decisions. You may feel that you do not have enough knowledge or information for this. Such feelings are common, and may well have been shared by the Viking engineers. There seems never to be enough information, yet choices must be made regardless. One of the arts of engineering is doing the best you can with what you do know and with the resources (always limited) available.

Present your recommendations, with brief justification, in the form of a short memorandum (maximum 2 typed pages) to your instructor, who again will play the role of NASA's Viking Project Office.

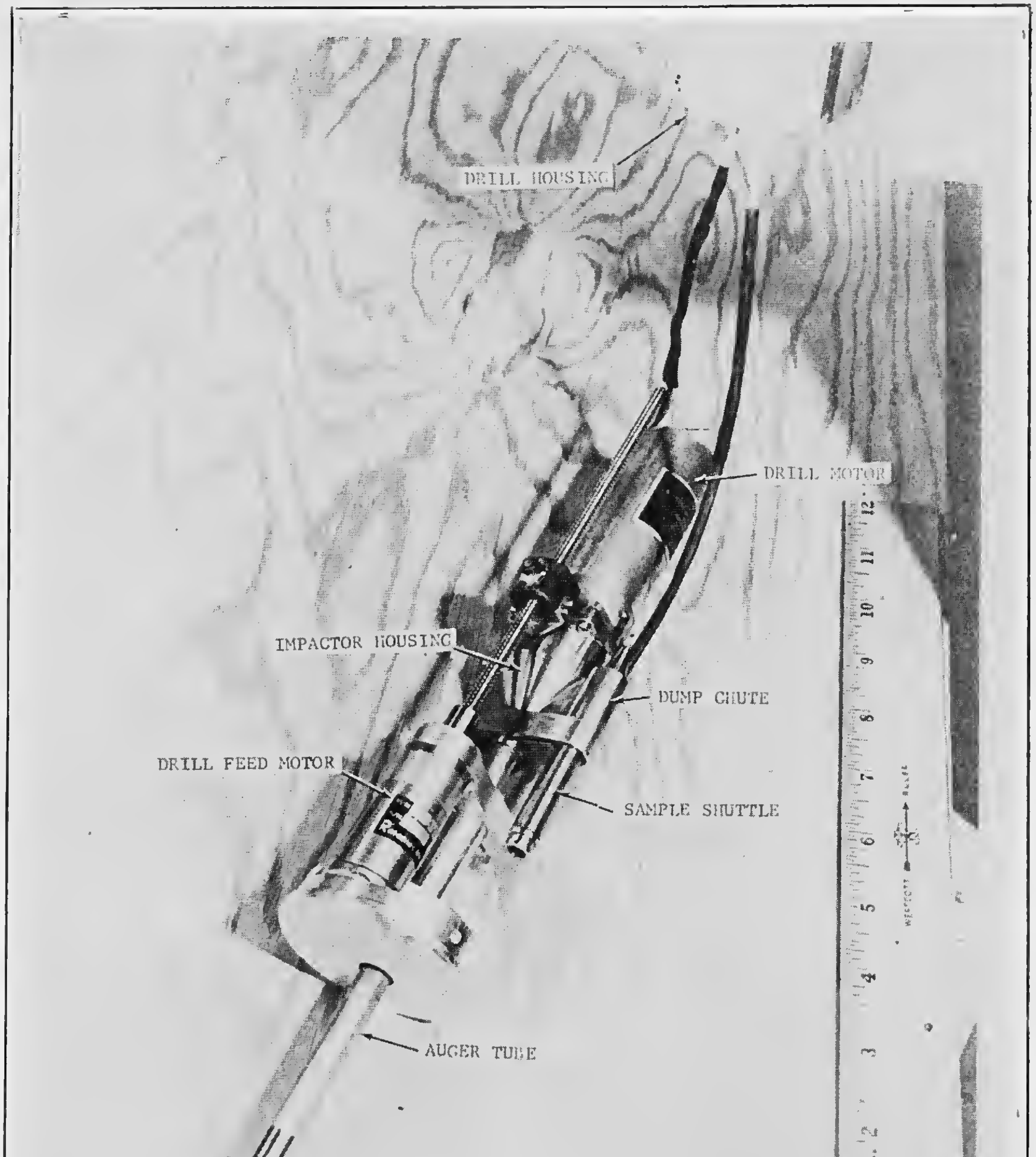


FIGURE 5
POWER HEAD WITH DRILL STRING

Exhibit H-2. Expected Improvement in Reliability from Incorporating Drill Sampler.

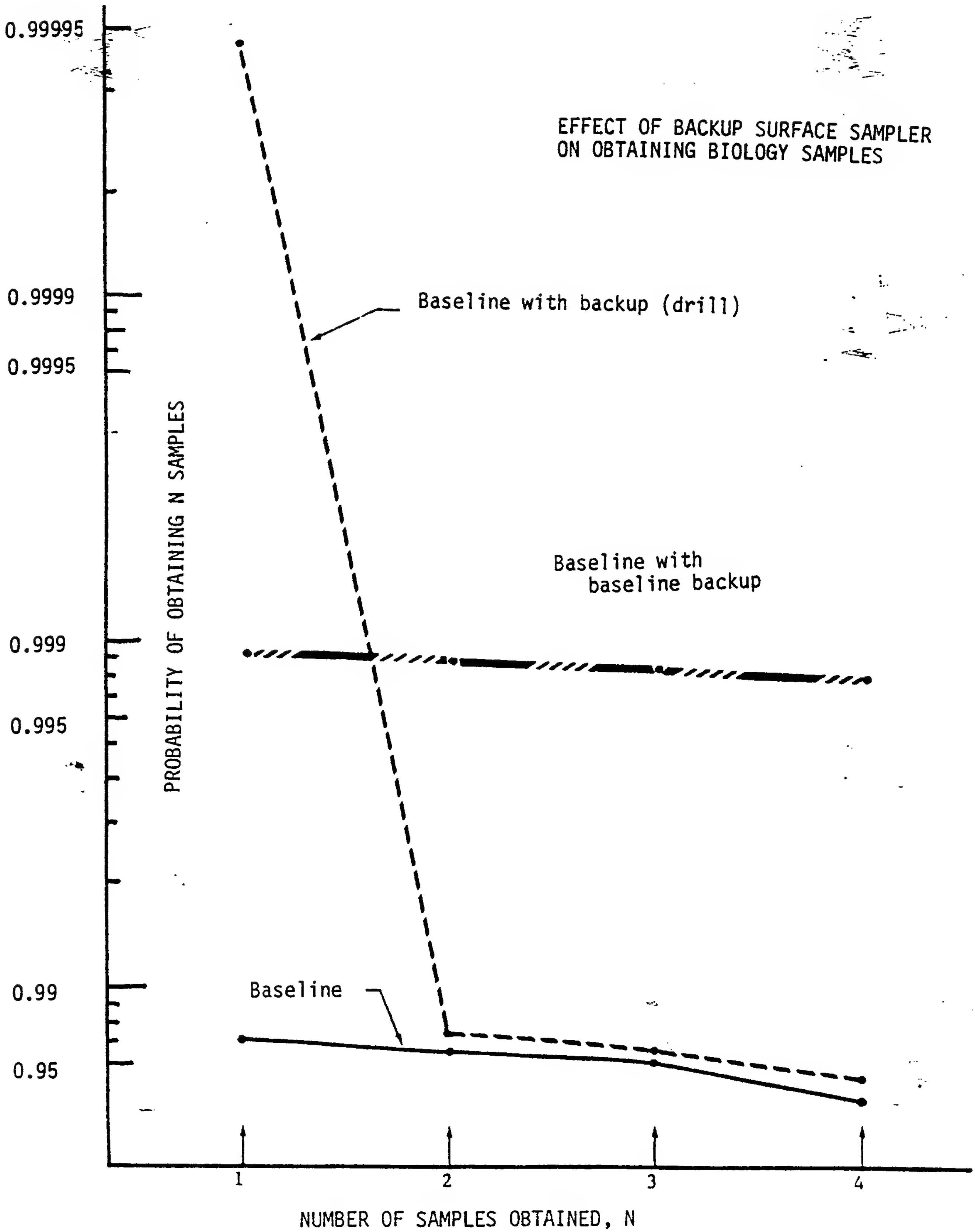


Exhibit H-3. Dust Chamber with Prototype Passive Collector in Place for Testing.

Exhibit H-4. Prototype Mortar-Launched Surface Sampler.

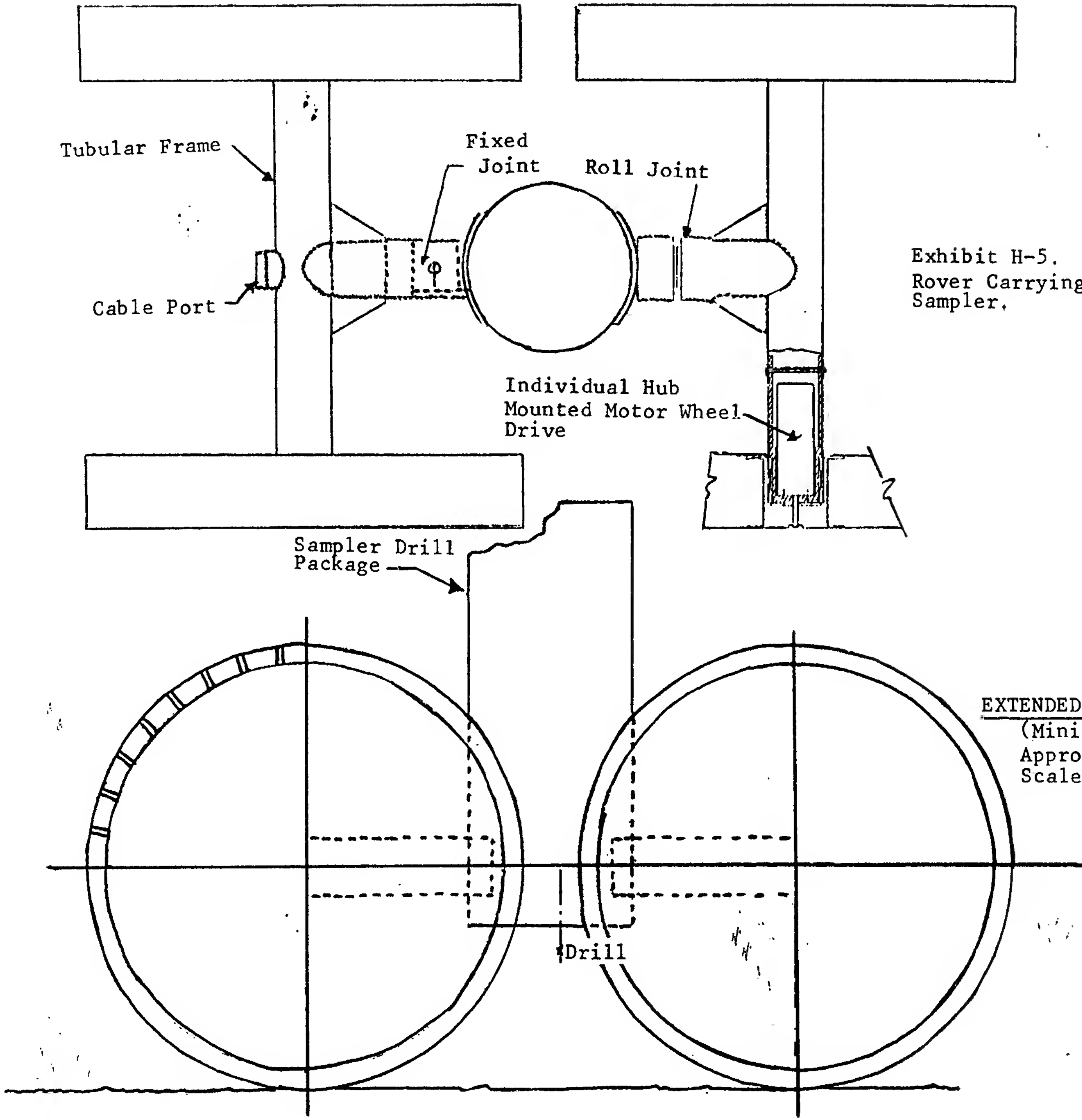


Exhibit H-5. Proposed Mars Rover Carrying Drill-Type Sampler.

EXTENDED SURFACE SAMPLER
(Mini-Drill Type)
Approx. Wt. 11 lbs.
Scale Full

DIGGING INTO MARS (I)

In the end, the only backup sampling capability on Viking was passive, provided by petal-like vanes surrounding the intakes for the science experiments. These are visible in Exhibit A-2 (first section of case). The primary function of these vanes is to act as wind deflectors, preventing soil samples from being blown away as they are dumped from the collector head. Don Crouch explained why the other options--a longer boom as well as the redundant samplers--were dropped. "The two main reasons were weight, plus a redesign of the lander engines. We already had weight problems with the soil sampler, and most of the backups would have added to these."

"The engine redesign was a real help in getting away from the need for long range sampling capability. One of the reasons for looking at long range samplers had been our fear that the exhaust plumes from the engines would contaminate the surface near the lander. The redesign involved replacing the single nozzle originally planned for each engine with 18 or 20 smaller nozzles. These would diffuse the plume. The new nozzles* were tested in a simulation chamber by lowering a mocked-up lander on cables with the engines going. This test was successful and relieved much of our concern about contamination."

"After these decisions, we spent a lot more time on testing of surface sampler components; but by late 1972 our course was set." The final design used a 10 ft seam-welded furlable tube boom similar, though not identical, to that shown in Exhibit E-1. The boom is extended by sprockets, which engage drive holes along its edges. The boom is furled by simply driving the take-up drum.

A prototype of the flight-ready SSAA is shown in Exhibit I-1. Enclosures for dust protection are added when the SSAA is installed on the lander. The final collector head design appears in Exhibit I-2, while a mock-up lander with the surface sampler boom extended is shown in Exhibit I-3.

Extensive analysis and testing preceded final decisions on many design features. A few examples will illustrate their range and variety. Test results were used to determine the final shape of the backhoe blade. Wind tunnel tests were used to study material transfer during sieving of soil from the collector head into the scientific experiments; these tests led to the petal-like vanes mentioned above. This, and other aspects of the operation of the SSAA were studied in

*Visible in Exhibit A-1.

simulated Mars gravity (3/8 g) using an Air Force low-gravity-test airplane.

The accuracy with which the collector head could be positioned was examined by tabulating all possible sources of positioning errors. Results of a portion of this analysis are given in Exhibit I-4. The last error source--temperature effect on boom bending--refers to the thermal strain which results if the top of the boom is heated by the sun--and thus expands--while the bottom remains cool.

A great deal of work went into the selection and design of the electric motors used in the lander--both for the SSAA and elsewhere. Several types of AC and DC motors were considered. The Viking engineering team drew heavily on experience accumulated with other spacecraft and with satellites. Hermetically sealed DC gearmotors, Exhibit I-5, were eventually selected for SSAA applications. Don Crouch explained some of the factors in this choice. "The primary reason for the sealing is to protect the brushes.* The atmospheric pressure on Mars turns out to be close to the critical pressure for arcing at the brushes--either above or below this pressure arcing would not be as much of a problem. The sealed portion of the motor is pressurized with dry nitrogen at one atmosphere."

The drive is taken through the hermetic seal by a magnetic coupling which will slip at a specified torque. This prevents overloading. If, for instance, the boom is extended or swung against a fixed obstacle, the coupling will slip before the boom can suffer permanent damage. The low speed, unsealed portion of the gear train--Gear Head in Exhibit -5--is protected by dust seals and O-rings. Forces required for various operations on Mars--digging, or pushing rocks, for example--are determined by monitoring the currents drawn by the motors. This data, which is important for determining various characteristics of the Mars surface, it is transmitted back to Earth for study.

Failure mode analysis is also an important aspect of a project such as Viking, where high reliability is required. Much effort went into examining the consequences of possible failures. Most serious would be failures preventing the delivery of soil samples. One of NASA's basic criteria for Viking was that no single failure should result in loss of scientific data. Because of the extensive redundancy, it would be possible to "work around" many failures. Nonetheless, stringent quality control measures were used to improve reliability. Don Crouch gave one example. "Say we have a subcontract with

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*The brushes are beneath the EMI filter in the drawing of Exhibit I-5. EMI stands for the electromagnetic interference. The filter prevents electrical noise created by the brushes from interfering with other electronics.

a company for switches. We'll have them set up a separate assembly line just for Viking switches, and test them all as they come off. This approach paid off in terms of the performance we've had on Mars."

A portion of the failure mode analysis presented at the surface sampler Preliminary Design Review is reproduced in ExhibitI -6. Note the ranking of the possible failures in terms of "criticality." One tool in such work is called worst case analysis. Here the worst possible combination of parameters in a given situation is examined. For example, these might be dimensions in the case of mechanical components. In an electrical system, they might be circuit parameters such as resistance and capacitance. Exhibit I-7 shows a page from a worst case analysis for the collector head.

At the peak of the SSAA program in 1972-73 there were about 50 people working on the boom and collector head, eight of them engineers. Many of the others were draftsmen making detail drawings. "We had to do two or three hundred details in a short period of time," said Don. Much of the effort during this period also went into further testing of qualification and flight units. In addition, there were further design reviews.

A Mechanical Design Status Review took place in January 1972, with the Critical Design Review (CDR) in March 1973. Both of these were for the surface sampler only. In between came many reviews for individual components and subsystems such as motors, solenoids, and the boom. Don said, "At a CDR, the detail drawings are all complete; you may even have had to release some for production. After the hardware is built there is a Preliminary Hardware Design Review--usually for qualification hardware. Here you review test procedures. Then come Flight Readiness Reviews, where you go through the results of the qualification tests and try to resolve any failures or anomolies. We also had prelaunch reviews at Cape Kennedy in January and February (1975)."

Instruction I

Little mention thus far has been made of the materials from which the SSAA would be constructed. Your next task is to investigate possible materials for collector head (scoop) components (ExhibitI -2) and for the mounting structure for the boom (Exhibit I-1). The materials used must be heat-sterilizable; another important requirement is light weight combined with high strength and stiffness. Quantities such as specific strength (yield strength or tensile strength divided by density) and specific stiffness (tensile modulus divided by density) can be used to compare materials for such applications. You should rank a variety of candidate materials in terms of specific strength

and stiffness, as well as any other properties you think will be important. From these lists choose suitable materials for the collector head and for the boom support structure.

Any technical library will have many text and reference books which will help you carry out this instruction. You may find the following particularly useful:

-- Metals Handbook, Vol. 1: Properties and Selection, American Society for Metals, 1961.

-- ASME Handbook: Metals Properties, McGraw-Hill, 1954.

-- Aerospace Structural Metals Handbook, Vol. I: Ferrous Alloys. Vol. II: Non-Ferrous Alloys, Syracuse University Press, 1963.

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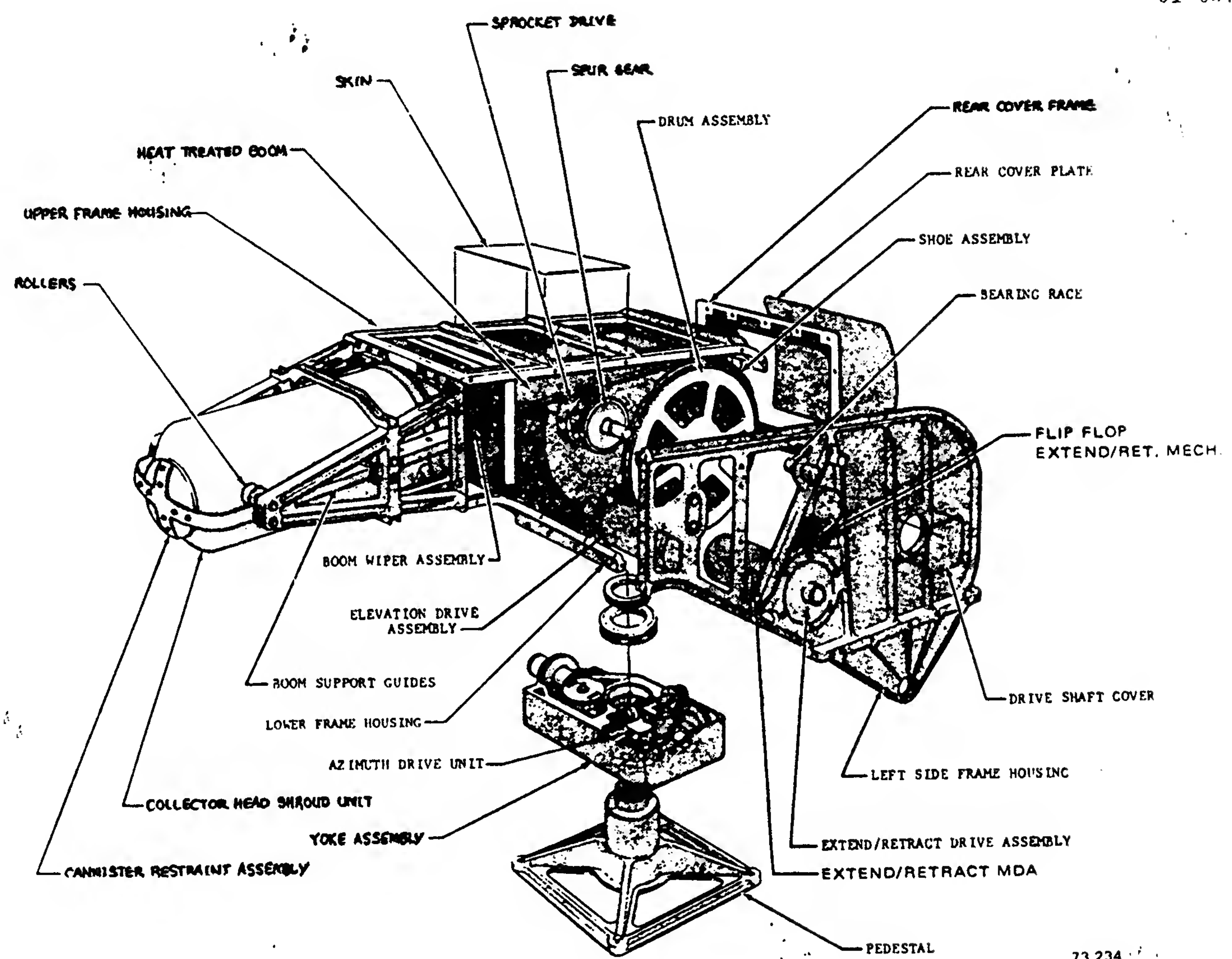


Exhibit I-1. Final Design Surface Sampler Acquisition Assembly.

COLLECTOR HEAD UNIT

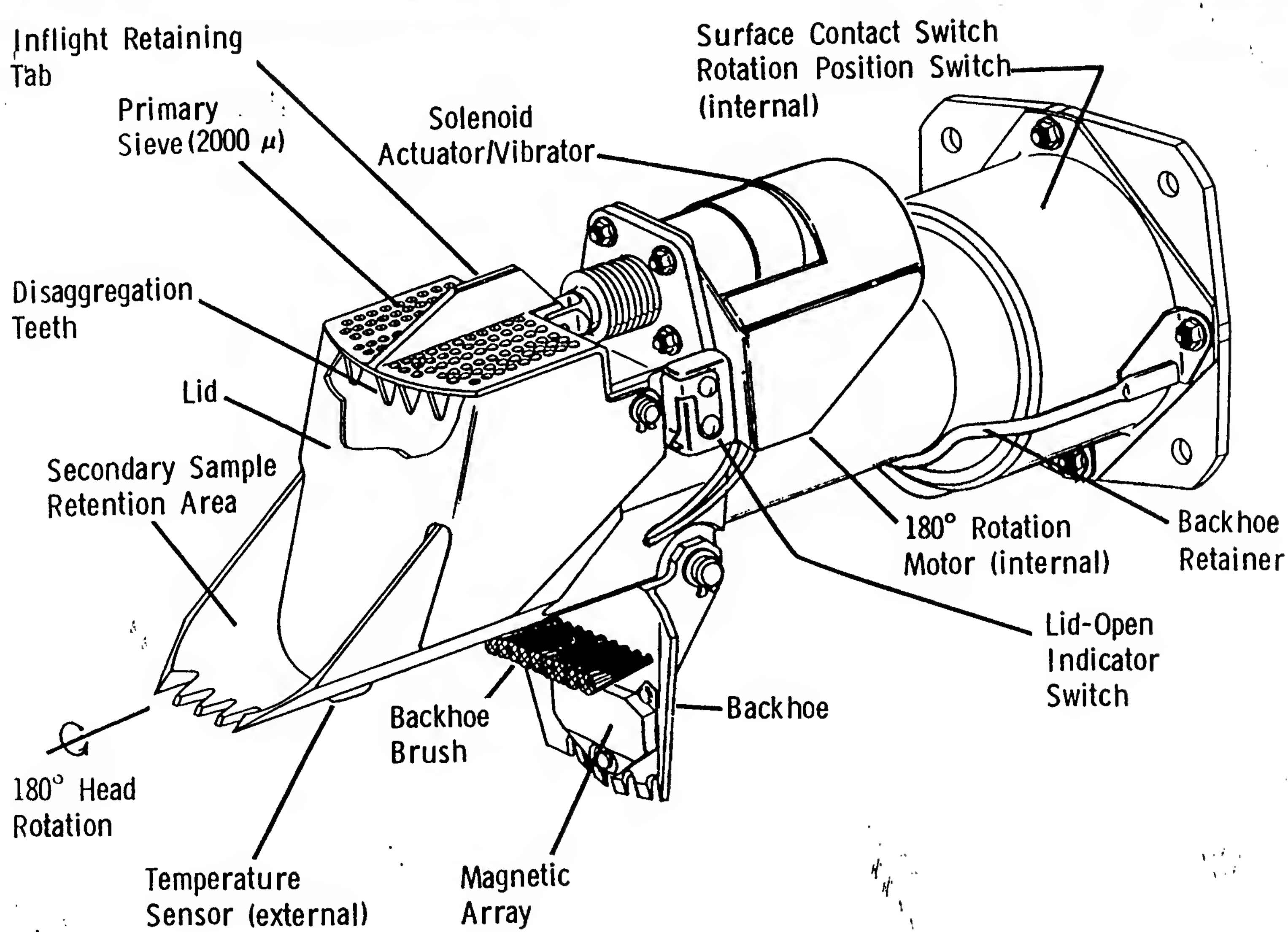
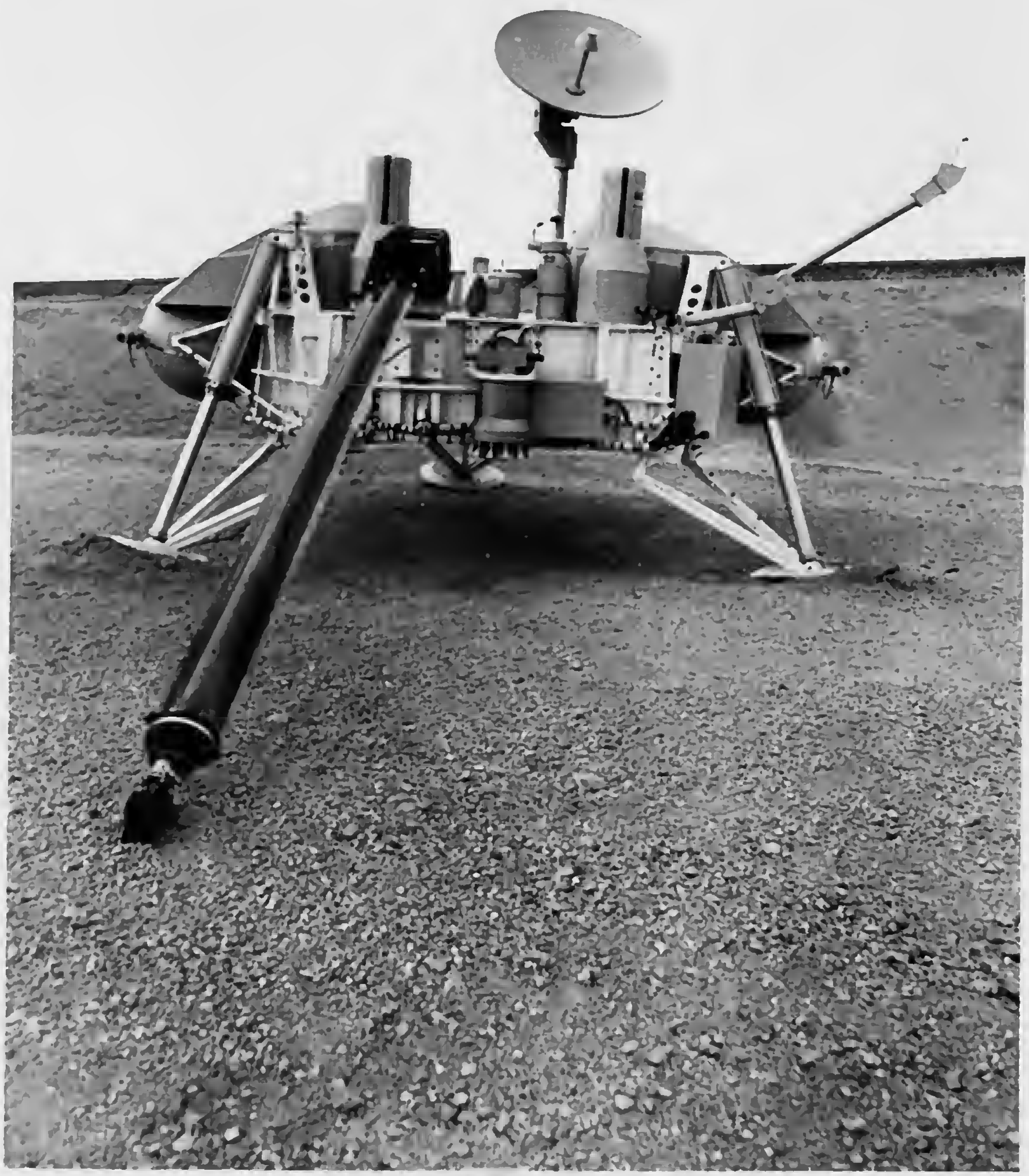


Exhibit I-2. Final Design Collector Head.



ERROR SOURCE	Unit	31 Inch Extension			60 Inch Extension			130 Inch Extension		
		Azi.	Elev.	Ext.	Azi.	Elev.	Ext.	Azi.	Elev.	Ext.
1. Electrical Controls (.674 bits)	Inches	.234	.234	.158	.453	.453	.158	.980	.980	.158
2. Boom Overtravel from motor turnoff	Inches	0	0	0	0	0	0	0	0	0
3. Tolerance on mounting dimension	Inches	0	0	0	0	0	0	0	0	0
				(calibratible)						
4. Tolerance from boom mounting position	Inches	0	0	0	0	0	0	0	0	0
				(calibratible)						
5. Gear backlash	Inches	.135	0	0	.263	0	0	.567	0	0
6. Bit error	Inches	.171	.171	.118	.331	.331	.118	.718	.718	.118
7. Ground Update Control	Inches	(not yet analyzed)								
8. Load bending effect	Inches	0	TBD	0	0	TBD	0	0	TBD	0
9. Lander tilt effects	Inches	0	0	0	0	0	0	0	0	0
				(updatable)						
10. Wind Forces	Inches	-	-	-	-	-	-	-	-	-
			(not yet analyzed)							
11. Temperature effect on boom bending ($\Delta T=50^oF$)	Inches	0	-.041	0	0	-.180	0	0	-.830	0
TOTAL POSITION ERROR (3 SIGMA)	Inches	.32	-.29	.20	.62	-.80	.20	1.34	-1.47	.20

Azimuth & Elevation - 1 bit = .636^o = tan (X^o) X extension "
Extend 1 bit = .235"

Exhibit I-4. Table of SSAA Positioning Errors.

CUTAWAY OF GEARMOTOR

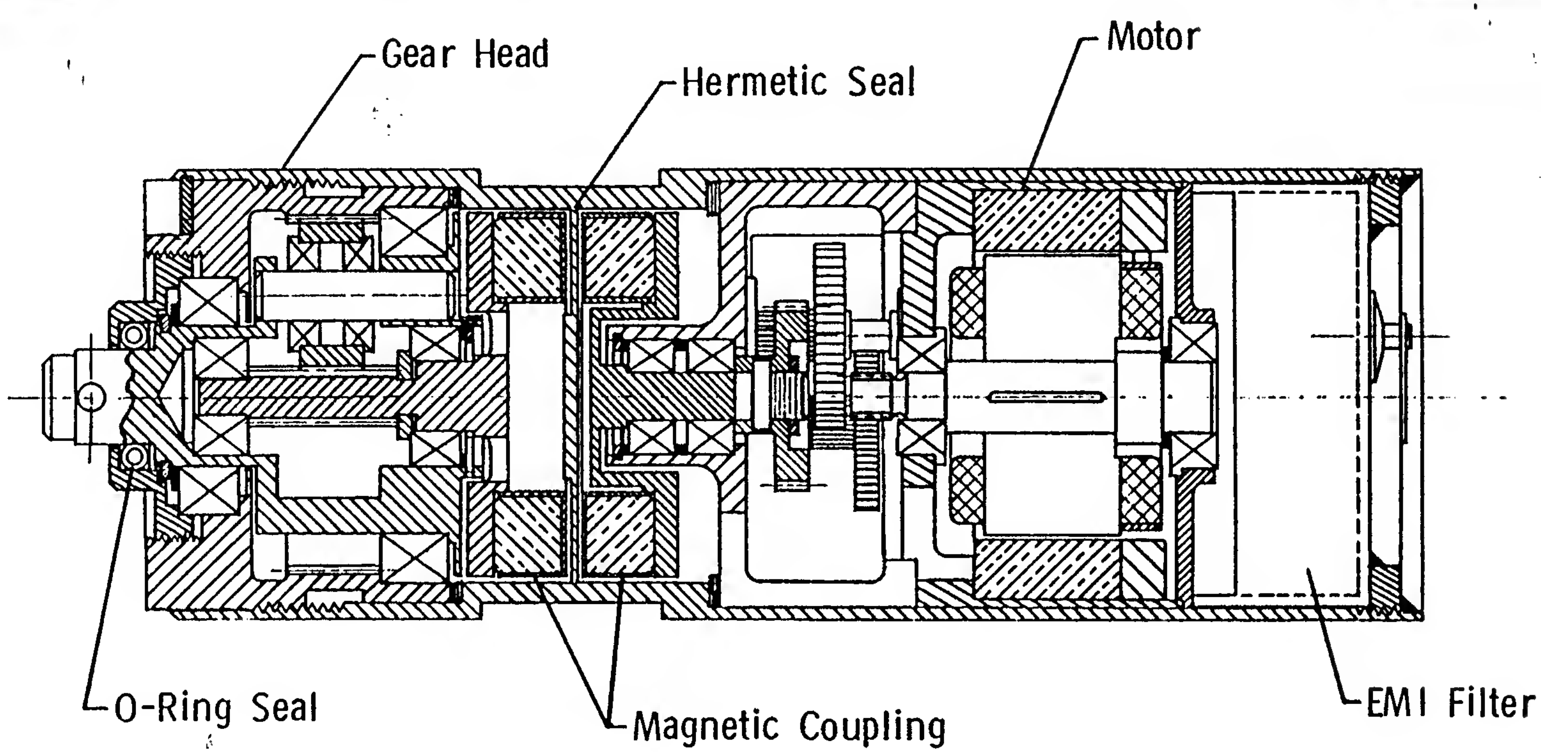


Exhibit I-5. Hermetically Sealed DC Gearmotor.

SUBSYSTEM Surface Sampler TABLE 6-2 (Sheet 1) DATE March 18, 1971

COMPONENT	FAILURE MODE	MISSION PHASE	FAILURE EFFECT	CRITICALITY*	COMMENTS
SSCA					
Power Supply	Loss of any electronic part	Landed Operation	Inability to obtain samples	3	
Controls	Loss of any electronic part	Landed Operation	Inability to obtain samples	3	
Data Processing	Loss of any electronic part	Landed Operation	Likely to not obtain samples	3	Depending on failure, may be able to continue operation
ACQUISITION ASS'Y					
Boom Unit	1. Motors	Landed Operation	Inability to obtain sample	3	
	2. Potentiometer	Landed Operation	Inability to obtain sample (Improper elect-feedback)	3-6	May be able to continue limited sampling by using limit switches or cameras
	3. Overload Sensors	Landed Operation	Damage to boom (Potential)	3-6	May be able to continue sampling by normal SSCA control
	4. Limit Switches	Landed Operation	Damage to boom/gimbals	3-6	May be able to continue sampling by normal SSCA control

* Criticality Definition

1. Single failure prevents soft landing
2. Single failure prevents obtaining any entry and/or landed science data
3. Single failure prevents obtaining particular science data
4. Single failure prevents obtaining landed engineering data
5. Single failure prevents obtaining entry or cruise engineering data
6. Alternate mode exists providing failure compensation

Exhibit I-6. Portion of Preliminary Failure Mode Analysis.

BY TIMBROOK DATE 6-16-2 SUBJECT WORST CASE ANAL DIMENSIONAL STACK COLLECTOR HEAD [redacted] SHEET NO. 4 OF

CHKD. BY REV DATE 2-15-73 JOB NO.

ROTATION MECHANISM

(3) BEARING CLEARANCE (TOTAL - RADIAL)

$$\text{ACTUAL} = 1.500^{+.002}_{-.000} - \left(1.362^{+.005}_{-.000} + 2(.064^{+.000}_{-.010})\right)$$

$$(3)_{MAX} = 1.502 - (1.362 + .108)$$

$$= 1.502 - 1.470 = \underline{.032}$$

$$(3)_{MIN} = 1.500 - (1.367 + .128)$$

$$= 1.500 - 1.495 = \underline{.005}$$

BEARING CLEARANCE ON MOTOR HOUSING

$$\text{ACTUAL} = 1.362^{+.005}_{-.000} - 1.360^{+.000}_{-.010}$$

$$\text{MAX} = 1.367 - 1.350 = \underline{.017}$$

$$\text{MIN} = 1.362 - 1.360 = \underline{.002}$$

(4) BEARING CLEARANCE - AFT (TOTAL - RADIAL)

$$\text{ACTUAL} = 1.500^{+.002}_{-.000} - \left[1.360^{+.000}_{-.010} + 2(.064^{+.000}_{-.005})\right]$$

$$(4)_{MAX} = 1.502 - (1.350 + 2(.059))$$

$$= 1.502 - 1.468 = \underline{.034}$$

$$(4)_{MIN} = 1.500 - (1.360 - 2(.064))$$

$$= 1.500 - 1.488 = \underline{.012}$$

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ExhibitI -7. Page from Collector Head Worst Case Analysis.

DIGGING INTO MARS (J)

Most of the collector head parts were made from magnesium, with components such as pins and springs of stainless steel. The original plan was to use magnesium for many other parts also, and beryllium was even considered to save weight. "But we ran into a lot of problems with creep and stress relaxation of magnesium during bake-out,*" Don Crouch explained. This caused loss of fit of parts, loss of bolt tension, and so on. Of course once the parts are cleaned and sterilized we can't go back in and tighten things up again. At first we tried magnesium-thorium alloys to get improved stress relaxation characteristics. I think we bought up most of the thorium-magnesium in the country. Then, near the midpoint of the program, we got a weight bonus on the lander of about 100 lb. This was because of new knowledge of the atmosphere on Mars sent back by Mariner 9. It turned out the atmospheric pressure was 5 or 6 millibars rather than 2, allowing a better aerodynamic landing trajectory. At this point we went to aluminum instead of magnesium for most of the parts in the gimbal mount." 6061-T6 alloy was used in the majority of these.

Other materials problems were encountered with the furlable tube boom, for which Carpenter Custom 455 stainless steel was ultimately chosen. Custom 455 contains 12% chromium, 8 1/2% nickel, plus a number of other alloying elements, and can be heat treated to strength levels which are unusually high for a stainless steel. "This alloy wasn't very well characterized at low temperatures," Don said. "It would crack and split near the welds when flattened and rolled up. It took 20 or 25 stabs to get the heat treatment and welding right. We wanted at least 100 cycles without cracking. It would be fine at room temperature, but sometimes fail after 8 or 10 cycles at simulated Mars temperatures."

"One of the things we found was that the properties seemed to go through a trough at about -70°F, so we did most of our testing there, although the qualification tests were at -190°F. Eventually we got a boom that's good for about a thousand cycles, but we spent a year dealing with this set of problems."

Much of the testing and development on the boom material was carried out by the subcontractor chosen to supply the booms, Atlantic Research Corporation.** "Six or seven booms were actually made," Don

*Creep is continued deformation under nominally constant load or stress. It is often encountered at elevated temperatures--here during heating for sterilization (bake-out)--where materials in any case suffer a loss of strength. Stress relaxation is a parallel phenomenon in which the stress or load will decrease if the deformation is held constant.

**During the course of the Viking project, the name of this company was changed to Celesco Industries.

said. "We really only needed four--for the two landers plus spares--but originally the meteorology boom was to be identical to the surface sampler boom. This was later changed, and we ended up with some extras."

The two strips of stainless steel from which the boom tubes are welded were tapered both from side-to-side and from end-to-end to save weight. "The tube is 7 mils* thick at the inboard end and only 4 mils thick at the collector head," Don said. "This gives an approximately constant bending stress along the tube." The tapering is done by chemical milling. In this process, a chemical reagent such as an acid is used to etch away material at a controlled rate. The boom, collector head, and mounting unit finally weighed about 23 lb.

Lubrication of moving parts brought another set of problems. Prohibition of organic materials severely restricted the possible lubricants. In some cases unlubricated anodized surfaces were specified. Anodizing is a process which forms a hard oxide layer on aluminum or magnesium. Other components used proprietary molybdenum disulfide treatments or graphite "microseal" coatings. However neither of these could be used near the science experiments. "Some of the sliding shuttles in the experiments really gave us headaches," Don recalled. "They would be OK when we tested them in the lab, but after going through all the stages of cleaning and sterilizations they would bind and jam."

Assembly of the surface samplers took place in a clean room, with a series of degreasing and cleaning operations as the work progressed. The basic cleanliness target was 1 nanogram of foreign matter per cm^2 of surface area. "After checkout, the actual flight hardware was disassembled and cleaned again," Don said. "The effluent would be analyzed periodically during the cleaning, which was done in a unique facility at White Sands missile range. Then the parts were baked-out and put back together. At this point there's another solvent cleaning step and then a 1 week bake-out. This continues as the assembly is built up; it takes longer and longer to get the solvent out because of the tortuous paths, so hot helium is used as a flushing agent. When an assembly such as the boom unit is completed, it is sealed, pressurized with ultrapure nitrogen, and then shipped to Cape Kennedy under 24 hour surveillance."

"Getting those parts to move freely after they were squeaky-clean was probably our biggest single problem," Don continued. "After assembly, and the launches at Cape Kennedy, we had about a year to rethink strategy for the operations on Mars. Software development

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*1 mil = .001 in.

had been lagging, and we went back to work on that. We were even able to go back to 8 hour days for a while."

"Martin Marietta gives the key engineers on a project like this--for instance the Product Integrity Engineers working under the Project Engineer--responsibility from design, through test, right onto the Mars surface. Our operations were moved to JPL* where we could try out our software on a mock-up lander. We developed solutions to potential operation problems and made our decisions on how to work on Mars."

"Most of the memory of the guidance and control computer is needed initially for entry and landing," Don continued. "It did have instructions for a few elementary experiments loaded in so we might be able to get some data back if we were unable to uplink.** However once the lander was on Mars, we could wipe out all the entry and landing instructions and transmit commands for much more complicated experiments. Every command in these transmissions was first verified on the mock-up at JPL."

A typical surface sampler operation involves the following steps:

- -- commands (generally 30 to 80) are generated and verified at JPL
- -- commands are transmitted to the lander and stored in its computer
- -- the stored commands are then in return transmitted to Earth for verification
- -- the computer sends commands to the surface sampler; data generated (e.g. motor currents) is stored on a tape recorder
- -- the lander transmits the stored data to the orbiter where it is again stored on tape
- -- the orbiter transmits the data to Earth

There are twelve types of surface sampler commands: boom extend/retract; elevate/de-elevate; cw/ccw azimuth; cw/ccw collector head rotate; collector head open/close; 4.8/8.8 Hz collector head vibrations. Each command has the form of a 24 bit binary word, including quantitative position data if needed.

Surface sampler operations are summarized using the format shown in Exhibit J-1. This page deals with the jamming of the boom restraint pin on Viking 1 which was mentioned at the beginning of the case. The

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*Jet Propulsion Laboratory, Pasadena, California.

**Send communications from Earth to the lander. A downlink is a communication from the lander to Earth.

jam occured during ejection of the contamination control shroud which enclosed the collector head during flight. After the boom had jammed, the conditions were simulated on the mock-up lander at JPL and a command sequence to free the boom tested and uplinked to the lander. Don Crouch said, "We had never experienced that type of jam in any of our testing. I think maybe it was a matter of a small difference in dimensions between the parts that flew on Viking 1 and those on the test units."

While a number of other anomolies or failures were encountered during operation of the two landers on Mars--for instance, a probable microswitch failure on Viking 2, and a short circuit-to-ground in one of the boom cable conductors on Viking 1--none of these interfered seriously with the conduct of the experiments, the flexibility and redundancy of the surface sampler allowing alternate modes of operation. Two years after reaching Mars, both surface samplers continue to function after executing a combined total of 13,000 commands. A pair of photographs taken on Mars by Viking 2 are shown in Exhibit J -2. The boom and collector head can be seen at left.

Don Crouch offered these concluding comments to young engineers. "It's important to keep your options open as long as possible when working on a project like this. There's a great temptation to latch onto the first good idea that comes along, but if you get too far down one path and it doesn't work out, then it's awfully hard--and expensive--to turn around and take a new approach. This is especially true with time constraints like we had on Viking."

SEQUENCE: VL-1 / SOL 2 CHSU Eject Sequence SIP: ICL U/L REV 2

UPLINK SUMMARY: Sequence controlled by preprogrammed ICL

DOWNLINK SUMMARY:

POWER ON: 02/10:20:50 LLT 204/07:19:54 UTC 00:19:54 JUL 22 PDT

POWER OFF: 02/10:35:32 LLT 204/07:34:36 UTC 00:34:36 JUL 22 PDT

COMMANDS ISSUED: 13 DATA FRAMES EXPECTED/RECEIVED 12/12

SAMPLING STRATEGY (BOOM COORDINATES):

BACKHOE STROKE			SAMPLING STROKE		
AZIMUTH:	N/A	DEG.	AZIMUTH:	N/A	DEG.
EXT. AT SURCON:	N/A	IN.	EXT. AT SURCON:	N/A	IN.
SURCON ELEV:	N/A	DEG.	SURCON ELEV:	N/A	DEG.
BACKHOE TO:	N/A	IN.	EXT. TO:	N/A	IN.
			RETRACT TO:	N/A	IN.

SPECIAL NOTES: Shroud ejected with boom positioned at 255.4° AZ., -40.1° Elev, and 6.0" Ext.

SAMPLING CURRENTS:

SAMPLING EXTENSION: I-1 N/A MA I-2 N/A MA FORMAT 5? No

ELEVATION FROM SITE: I-1 N/A MA I-2 N/A MA

TEMPERATURE RANGE: -9 to -8° °F (C.H.) +20 to +23° °F (BIOL. PDA)

Analysis of SSCA TM and the MRO revealed that twelve (12) commands of the seventeen (17) command sequence were properly executed. During execution of the 13th command (Retract from 4.1 to 2.0 inches) the boom failed to attain position and a "No-Go" was generated when the GCSC issued the 14th command. The SSCA electronics automatically powered down, and the boom remained parked in the shroud eject position.

Subsequent analysis of the anomaly (See Section 5.0 for details) revealed that the problem was caused by a jamming of the launch and cruise boom restraint pin, which did not fall free from its guide during execution of the 6th command (Extend from 2.3 to 6.0 inches). When the boom was commanded to retract during the 13th command, the unreleased latch pin misaligned and jammed against the boom pin support structure. With an assumed retraction rate of 1 inch/second, the boom extend/retract motor probably clutched for 66 seconds before the next command was issued.

Figure 4-1 shows a Sol 2 image verifying the successful CHSU ejection and a Sol 10 image showing the shroud on the surface behind Leg No. 3.

Exhibit J-1. Report Page Dealing with Surface Sampler Operation During Which Boom Restraint Pin Jammed on Viking 1's Second Day on Mars.

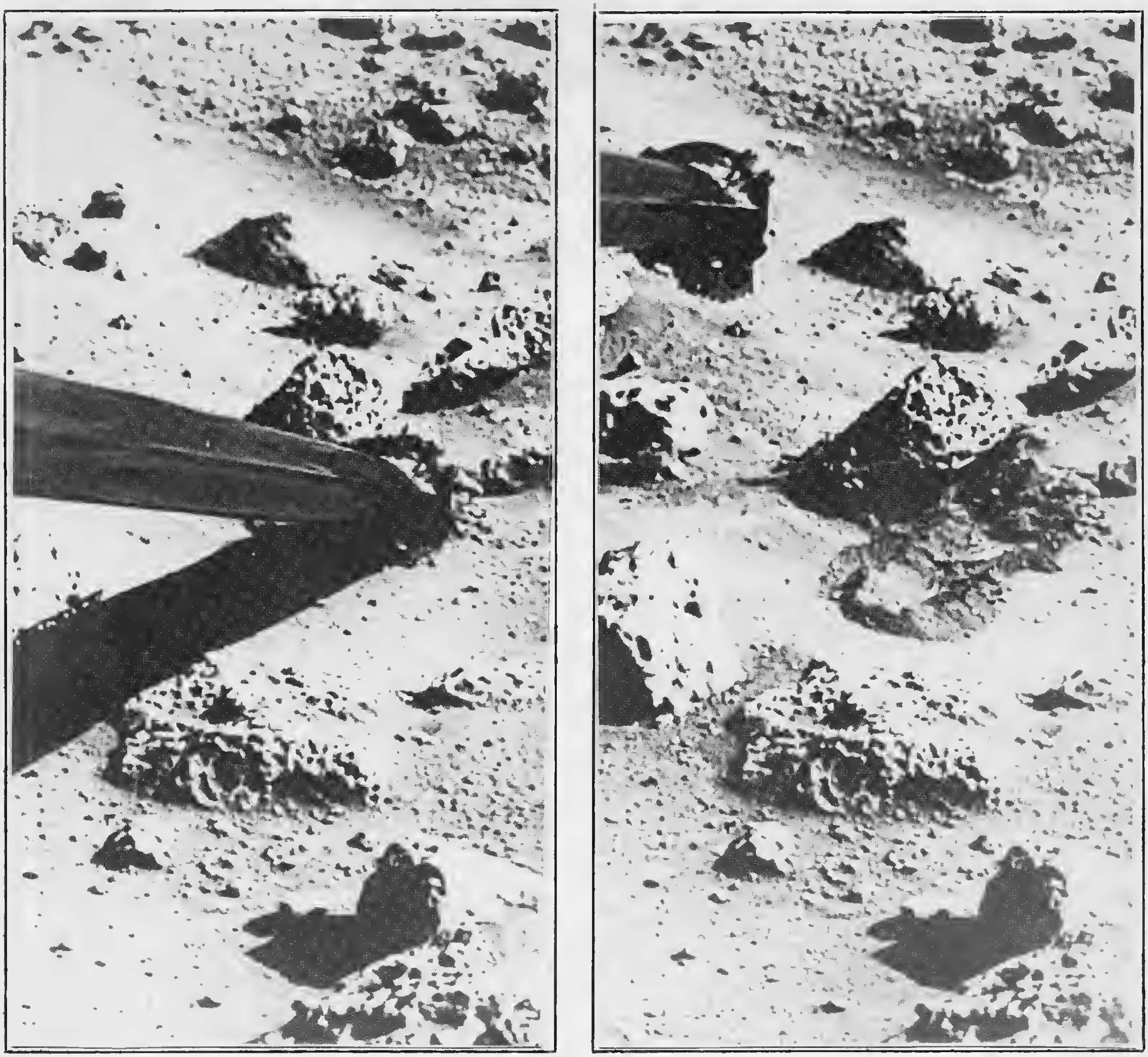

Exhibit J-2. Photographs of Viking 2 Rock Push, October 8, 1976. Photograph on the left shows Lander 2 surface sampler boom in the process of moving a rock. Photograph on the right shows displaced after move.

Instructor's Note

for

CENTER INDUSTRIES CORPORATION:
Adaptation of a Tube Beader
for Operation by the Handicapped

and

DIGGING INTO MARS:
The Viking Surface Sampler

These cases differ in several respects from the norm primarily because they are written for use in large classes (50 or more) of freshman/sophomore students. With so many students, discussion involving the whole class is difficult; furthermore, the instructor may be hard-pressed to respond to the number of questions and the need for explanation to lower level students. For these reasons a good deal of explanation has been built into the cases to make them at least moderately self-contained. This can be skimmed or skipped by more advanced students.

In their use with lower level students at Wichita State University, these cases form the basis of projects lasting about a month. This is the reason for their considerable length and the large numbers of sections into which they have been subdivided. Students work on the cases in groups, typically of 5 to 7, during the class period, while the instructor circulates from group to group. At frequent intervals the entire class is called together and individual groups make presentations to the rest of the class. Obviously there are many ways of modifying the instructions or questions for other modes of use and to correspond to the time available and the level of the students.